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PATENT APPLICATION

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:

TAKEO TSUKAMOTO

Application No.: 09/941,595

Filed: August 30, 2001

For: ELECTRON-EMITTING DEVICE,)
ELECTRON SOURCE AND :
IMAGE-FORMING APPARATUS,)
AND METHOD FOR MANUFAC- :
TURING ELECTRON EMITTING)
DEVICE :

Examiner: NYA

Group Art Unit: 2879

November 29, 2001

Commissioner for Patents
Washington, D.C. 20231

INFORMATION DISCLOSURE STATEMENT

Sir:

In compliance with the duty of disclosure under 37 C.F.R. § 1.56 and in accordance with the practice under 37 C.F.R. §§ 1.97 and 1.98, the Examiner's attention is directed to the documents listed on the enclosed Form PTO-1449. Copies of the listed documents are also enclosed.

For the concise explanation of relevance for the non-English documents, the Examiner is respectfully referred to the English Abstracts attached thereto, and for document 11-194134, the Examiner is also respectfully referred to EP 0 913 508 A2, cited in the Information Disclosure Statement filed on August 30, 2001.

The Examiner's attention is also directed to the following U.S. applications:

<u>APPLICATION NO.</u>	<u>FILING DATE</u>	<u>GROUP ART UNIT</u>
09/191,342	11/13/98	2879
09/941,780	8/30/01	2817
09/940,642	8/29/01	2879
09/940,643	8/29/01	2852
08/781,206	1/10/97	2879

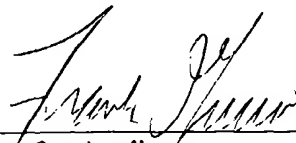
A copy of each cited Application is enclosed.

CONCLUSION

It is respectfully requested that the above information be considered by the Examiner and that a copy of the enclosed Form PTO-1449 be returned indicating that such information has been considered.

Applicant's undersigned attorney may be reached in our New York office by telephone at (212) 218-2100. All correspondence should continue to be directed to our address given below.

Respectfully submitted,



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ELECTRON-EMITTING DEVICE
AND PRODUCTION METHOD THEREOF



BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to an electron-emitting device and a production method thereof and, more particularly, to an electron-emitting device having a lower electrode, an insulating layer having pores, and an upper electrode stacked in this order on a substrate, and a method for producing the electron-emitting device.

Related Background Art

The conventionally known electron-emitting devices are generally classified under two kinds, thermionic emission devices and cold cathode emission devices. The cold cathode emission devices include field emission type (FE type) devices, metal/insulator/metal type (MIN type) devices, surface conduction electron-emitting devices, and so on.

The FE type devices are disclosed, for example, in W. P. Dyke & W. W. Dolan, "Field emission," Advance in Electron Physics, 8, 89 (1956) or in C. A. Spindt, "PHYSICAL Properties of thin-film field emission cathodes with molybdenum cones," J. Appl. Phys., 47, 5248 (1976).

The tip of an electron-emitting body of the

field emission type electron-emitting devices is one called a cone having the three-dimensionally sharp-pointed shape and an electron beam is emitted from the tip of the cone by placing a strong electric field
5 between a gate electrode with an aperture, disposed above the cone, and an electron-emitting region.

In order to overcome the problem in the production method of the above field emission devices, which is the need for complicated steps and expensive
10 apparatus for forming a recessed portion for formation of the electron-emitting region, Japanese Laid-open Patent Applications No. 5-198252 and No. 5-211029 describe examples in which holes of an anodic oxide film of aluminum are used as apertures of the gate
15 electrode and in which electron-emitting regions are formed in the holes of the anodic oxide film. These conventional examples will be described referring to Figs. 32 and 33.

Fig. 32 is a sectional view of the electron-emitting device in Japanese Laid-open Patent
20 Application No. 5-198252. Fig. 33 is a sectional view of the electron-emitting device in Japanese Laid-open Patent Application No. 5-211029. In Fig. 32, reference numeral 161 designates an insulating substrate, 162 an
25 electroconductive layer, 163 an insulating film, 164 through holes, 165 the gate electrode, and 166 cathodes. The insulating film 163 is the anodic oxide

film of aluminum and the tip of the cathodes 166 is of the cone shape similar to that of the electron-emitting body of the field emission devices. In Fig. 33, reference numeral 171 designates a metal layer, 172 the
5 Al anodic oxide film, 172a micropores, and 173 cylindrical electrodes. The application describes that in Fig. 33 the distance can be made constant between the cylindrical electrodes 173 and the gate electrode or between the needlelike electrodes and the anode
10 electrode, so as to make electron emission efficiency constant.

The MIM type devices are disclosed, for example, in C. A. Mead, "Operation of Tunnel-Emission Devices," J. Appl. Phys., 32, 646 (1961).

15 Recent researches on the MIM type are seen in Toshiaki Kusunoki, "Fluctuation-free electron emission from non-formed metal-insulator-metal (MIM) cathodes fabricated by low current anodic oxidation," Jpn. J. Appl. Phys. vol. 32 (1993) pp L1695, Mutsumi Suzuki et
20 al., "An MIM cathode array for cathode luminescent displays," IDW '96 (1996) p529, and so on.

An MIM type electron-emitting device according to Kusunoki or Suzuki et al. described above will be described referring to Fig. 34. Fig. 34 is a schematic
25 sectional view of the MIM type electron-emitting device. In the same figure, reference numeral 1 denotes a substrate, 2 a lower electrode, 3 an

insulating layer, and 4 an upper electrode. The electron-emitting device is made by a production method for first forming SiO_2 on the Si substrate by sputtering, depositing Al as the lower electrode, 5 further forming an anodic oxide film of high quality in the thickness of 5.5 nm while controlling oxidation rates, using ethylene glycol and tartaric acid, and thereafter forming Au of the upper electrode in the thickness of 9 nm. It is described that good electron 10 emission characteristics were achieved by applying voltage between the anode of the upper electrode and the cathode of the lower electrode thus formed. Specifically, according to Kusunoki et al., negative resistance does not appear in the device current 15 flowing against the voltage applied to the device. The "negative resistance" herein is a phenomenon in which the device current decreases as the device voltage increases. In addition, fluctuation does not occur in the emission current. Here, the "fluctuation" means 20 temporal change of the emission current. It is also described that dependence of the emission current on the device voltage varies depending upon the thickness of the insulating layer and that the thicker the insulating layer, the higher the device voltage that 25 has to be applied. It is further described that with anodic oxide films made at high oxidation rates, the negative resistance appears in the electron emission

characteristics and the fluctuation occurs large.

An example of the surface conduction electron-emitting device with improved electron emission characteristics is described in Japanese Laid-open Patent Application No. 9-82214. This will be described referring to Figs. 35A and 35B. In the figures, reference numeral 191 denotes a substrate, 192 an electron-emitting region, 193 an electroconductive film, 194 a cathode device electrode, 195 an anode device electrode, 196 a fissure, and 197 a field correcting electrode. In the surface conduction electron-emitting device of this example, electrons emitted move in an electric field established by the cathode and the anode and a singular point of the electric field above the anode device electrode affects the ratio of electrons reaching the anode electrode, provided to sandwich a vacuum with the electron emitting element i.e., the electron emission efficiency. This device is an example in which the field correcting electrode is provided outside the device electrodes in order to improve the electron emission efficiency.

SUMMARY OF THE INVENTION

According to the studies by Spindt et al., the conventional FE type electron-emitting devices, however, had a problem of a spread of the electron

beam, which was hindrance against enhancement of definition. In the example of application of the holes of the anodic oxide film to the apertures of the gate electrode, there remained a problem of poor
5 repeatability in formation of the cone of the electron-emitting region. In the example in which the electron-emitting regions were formed in the cylindrical shape, there also arose problems of poor repeatability of the electron emission characteristics and high driving
10 voltage. In the surface conduction electron-emitting device provided with the correcting electrode, the electron emission efficiency was increased, but the potential of the correcting electrode was high, which was a problem in driving.

15 In the conventional MIM type electron-emitting devices, first, the thickness of the insulating layer was thin, several nm, and the thickness greatly affected the electron emission characteristics. In an electron source equipped with many devices, variations
20 in the thickness of the insulating layer are directly bound to variations in the emission current, so that control of variations is difficult. When an image pickup device or an image forming device is constructed using the electron source, there will arise a problem
25 of degradation of image quality. Second, the quality of the insulating layer did not affect only the electron emission characteristics, but also affected

the device current. In the case of the electron source equipped with many devices, variations in the quality of the insulating layer are directly bound to variations in the emission current. Particularly, in
5 the case of a large area, control of variations is difficult. In the image pickup device or the image forming device using the electron source, there will arise the problem of degradation of image quality. Third, repeatability was poor as to occurrence of the
10 negative resistance and occurrence of the fluctuation of the device current and control thereof was difficult.

In the conventional surface conduction electron-emitting device provided with the correcting
15 electrode, the electron emission efficiency was increased, but the potential of the correcting electrode was high, which was the problem in driving.

An object of the present invention is thus to provide an electron-emitting device having stable
20 electron emission characteristics with less variation that can achieve high electron emission efficiency, high definition, and low driving voltage.

For accomplishing the above object, the present invention provides an electron-emitting device
25 comprising a lower electrode, an insulating layer having a pore, and an upper electrode stacked in this order on a substrate, wherein a carbon deposit is

provided in the pore.

The present invention also provides an electron-emitting device comprising a lower electrode, an insulating layer having a pore, and an upper electrode stacked in this order on a substrate, wherein
5 an electron-emitting region is provided in the pore, the electron-emitting region is comprised of a small gap between the lower electrode and the upper electrode, and the small gap is formed by a rim-shape electroconductive body formed along an inner wall of
10 the pore, and the upper electrode.

The present invention further provides an electron-emitting device comprising a lower electrode, an insulating layer having a pore, and an upper electrode stacked in this order on a substrate, wherein
15 an electron-emitting body is provided in the pore, and where when a thickness of the upper electrode is t , a length of the pore is L , and a mean free path of electron transmission of the upper electrode is λ ,
20 they satisfy the following condition: $0.5 \times L \leq t < 2\lambda$.

The present invention also provides an electron-emitting device having a lower electrode, an insulating layer having a pore, and an upper electrode stacked in this order on a substrate, the electron-emitting device having an electron-emitting region in
25 the pore,

wherein the electron-emitting region is

comprised of a small gap between the lower electrode and the upper electrode and wherein a distance from the small gap to a top surface of the upper electrode is not more than 200 nm.

5 The present invention further provides a production method for producing an electron-emitting device comprising a lower electrode, an insulating layer having a pore, and an upper electrode stacked in this order on a substrate, the electron-emitting device
10 having a carbon deposit in the pore, the production method comprising a step of forming the lower electrode of a metal or a semiconductor on the substrate, a step of forming an anodic oxide layer on a surface of the lower electrode, a step of producing the carbon deposit
15 in the pore of the anodic oxide layer by applying a voltage under existence of an organic material, and a step of forming the upper electrode.

 The present invention further provides a production method for producing an electron-emitting
20 device comprising a lower electrode, an insulating layer having a pore, and an upper electrode stacked in this order on a substrate, the electron-emitting device having a carbon deposit in the pore, the production method comprising a step of forming the lower electrode
25 of a metal or a semiconductor on the substrate, a step of forming an anodic oxide layer on a surface of the lower electrode, a step of forming the upper electrode

on the lower electrode after formation of the anodic oxide layer, and a step of producing a carbon deposit in the pore of the anodic oxide layer by applying a voltage to the upper electrode and the lower electrode under existence of an organic material.

In the electron-emitting devices of the present invention, the holes are formed in the porous structure in the insulating layer such as the oxide film formed by anodic oxidation, at least the carbon deposit being the electron-emitting body is formed in the holes of the porous structure, and the gap is provided between the lower electrode and the upper electrode; therefore, with application of the voltage between the lower electrode and the upper electrode so as to keep the upper electrode at a higher potential, the electrons injected from the lower electrode tunnel through the gap between the carbon, formed on the lower electrode, and the upper electrode into a vacuum, whereby the electrons are emitted.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A and Fig. 1B are a sectional view and a perspective view of an electron-emitting device in the first embodiment of the present invention;

Fig. 2A, Fig. 2B, Fig. 2C, and Fig. 2D are sectional views for explaining structures of the electron-emitting device of the first embodiment;

Fig. 3 is a flowchart of a process for producing the electron-emitting device of the first embodiment;

5 Fig. 4 is a sectional view of an anodic oxidation system used in production of the electron-emitting device;

Fig. 5 is a sectional view of a vacuum process system used in production of the electron-emitting device;

10 Fig. 6A and Fig. 6B are waveform diagrams of voltage pulses applied in a step of forming carbon in the pores of the anodic oxide layer;

Fig. 7A and Fig. 7B are a plan view and a sectional view of electron-emitting devices in Example 15 1 of the first embodiment;

Fig. 8A and Fig. 8B are graphs to show characteristics of electron-emitting devices in Example 1 of the first embodiment;

20 Fig. 9A and Fig. 9B are a sectional view and a plan view of an image pickup device in Example 3 of the first embodiment;

Fig. 10A and Fig. 10B are a sectional view and a plan view of a display device in Example 4 of the first embodiment;

25 Fig. 11A and Fig. 11B are a sectional view and a perspective view of an electron-emitting device in the second embodiment of the present invention;

Fig. 12A, Fig. 12B, Fig. 12C, and Fig. 12D are sectional views for explaining structures of the electron-emitting device of the second embodiment;

5 Fig. 13 is a sectional view for explaining the principle of operation of the electron-emitting device in the second embodiment;

Fig. 14 is a flowchart of a process for producing the electron-emitting device of the second embodiment;

10 Fig. 15 is a sectional view of another anodic oxidation system used in production of the electron-emitting device;

Fig. 16 is a sectional view of a columnar metal forming system used in production of the electron-emitting device;

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Fig. 17A and Fig. 17B are sectional views for explaining sectional configurations of the electron-emitting device of the second embodiment;

20 Fig. 18 is a graph to show the relation between electron emission efficiency and thickness of the upper electrode in the electron-emitting device of the second embodiment;

Fig. 19 is a graph to show the relation between electron emission efficiency and diameter of aperture in the electron-emitting device of the second embodiment;

25

Fig. 20A and Fig. 20B are a sectional view and

a perspective view of an electron-emitting device in the third embodiment of the present invention;

Fig. 21A, Fig. 21B, Fig. 21C, and Fig. 21D are sectional views for explaining structures of the electron-emitting device of the third embodiment;

Fig. 22A and Fig. 22B are sectional views for explaining other structures of the electron-emitting device of the third embodiment;

Fig. 23 is a flowchart of a process for producing the electron-emitting device of the third embodiment;

Fig. 24 is a graph to show the relation between electron emission current and thickness of the upper electrode in the third embodiment;

Fig. 25A and Fig. 25B are a sectional view and a perspective view of an electron-emitting device in the fourth embodiment of the present invention;

Fig. 26A and Fig. 26B are sectional views for explaining structures of the electron-emitting device of the fourth embodiment;

Fig. 27 is a sectional view for explaining the principle of operation of the electron-emitting device in the fourth embodiment;

Fig. 28 is a flowchart of a process for producing the electron-emitting device of the fourth embodiment;

Fig. 29A and Fig. 29B are sectional views for

explaining configurations of the electron-emitting device of the fourth embodiment;

Fig. 30 is a graph to show the relation between electron emission efficiency and thickness of the upper electrode in the electron-emitting device of the fourth embodiment;

Fig. 31 is a graph to show the relation between electron emission efficiency and diameter of aperture in the electron-emitting device of the fourth embodiment;

Fig. 32 is a sectional view of a conventional FE type electron-emitting device;

Fig. 33 is a sectional view of another conventional FE type electron-emitting device;

Fig. 34 is a sectional view of a conventional MIM type electron-emitting device; and

Fig. 35A and Fig. 35B are a plan view and a sectional view of a conventional surface conduction electron-emitting device.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiments of the present invention will be described by reference to the drawings.

[First Embodiment]

Fig. 1A is a schematic, sectional view to show an example of the electron-emitting device according to the present invention. Fig. 1B is a partly enlarged,

schematic view of part A of Fig. 1A. In Fig. 1A, numeral 1 designates a substrate, 2 a lower electrode, 3 an anodic oxide layer, and 4 an upper electrode. In Fig. 1B, numeral 5 represents pores in the porous structure, and 6 carbon electrically connected to the lower electrode.

The substrate 1 to be employed herein can be selected from quartz glass, glass with a decreased content of impurity such as Na, soda lime glass, a glass substrate obtained by depositing SiO_2 on soda lime glass by sputtering or the like, ceramics such as alumina, an Si substrate, an Si substrate with a deposited layer of SiO_2 , and so on. Particularly, when the substrate 1 is a semiconductor substrate, a driver or the like for driving the electron-emitting device can also be mounted simultaneously.

The lower electrode 2 is selected from metals, such as Al, Ta, Nb, Ti, Zr, Hf, or Si, and semiconductors that can undergo anodic oxidation. The thickness of the lower electrode 2 is properly determined according to the thickness of the anodic oxide layer, the electrical resistance of the lower electrode, and so on.

The anodic oxide layer 3 is formed by anodic oxidation of the lower electrode in part. In the anodic oxide layer 3 there exist regular or irregular pores 5. This will also be called porous structure in

the present specification. The regular or irregular pores 5 can be formed by selecting anodic oxidation conditions including a composition of an anodic oxidation bath, the temperature of the bath, the voltage, the time, etc., according to the material for the lower electrode 2. Preferably, the regular pores are selected. Diameters of the pores range from several ten nm to several hundred nm and depths thereof from several ten nm to several hundred nm. The density of the pores is 10^8 to 10^{12} pores/cm² and corresponds to the density of electron-emitting points. Here, an electron-emitting point indicates a small area where electrons are emitted. In each pore 5, carbon 6, which is an electron-emitting body electrically connected to the lower electrode 2, is deposited on the wall of hole or is formed in a pole shape filling a part of each pore. The carbon may also be formed in the similar fashion from the side of the upper electrode 4.

There is a gap created between the carbon, formed on the lower electrode 2, and the upper electrode or, in the case where the carbon is also formed from the side of the upper electrode 4, between the carbon from the upper electrode 4 side and the carbon formed on the lower electrode 2. This gap is preferably several nm to several ten nm, and is properly determined according to the time of the step of applying the voltage to the upper electrode and

lower electrode under existence of the organic material detailed hereinafter, the voltage applied, and so on.

The upper electrode is formed on the anodic oxide layer and is preferably made of a metal with
5 excellent electron transmission characteristics, for example, Al.

Structural examples of the above electron-emitting device of the present invention will be explained using the schematic sectional views of Figs.
10 2A to 2D. In Figs. 2A to 2D, the same portions as those in Figs. 1A and 1B are denoted by the same reference numerals. There are four kinds of structures illustrated in Figs. 2A to 2D, but other structures may also be employed, without having to be limited to these
15 illustrated structures. The following describes examples using the metal for the upper electrode and the lower electrode, but they may also be made of a semiconductor. The structure of Fig. 2A is metal (lower electrode) 2 / metal oxide layer 3 / pores, each
20 having an electron-emitting body 6 / vacuum / metal (upper electrode) 4. The structure of Fig. 2B is metal (lower electrode) 2 / pores, each having an electron-emitting body 6 / vacuum / metal (upper electrode) 4. The structure of Fig. 2C is metal (lower electrode) 2 /
25 metal oxide layer 3 / pores, each having an electron-emitting body 6 / vacuum / metal (upper electrode) 4 formed in regions except for regions above the pores.

The structure of Fig. 2D is metal (lower electrode) 2 / pores, each having an electron-emitting body 6 / vacuum / metal (upper electrode) 4 formed in regions except for regions above the pores.

5 In the structures of Fig. 2A and Fig. 2C, the metal oxide layer 3 is obtained on the occasion of anodic oxidation of the lower electrode, and two structural regions, a dense film structural region without pores and a film structural region with pores, 10 can be obtained in this metal oxide layer 3, depending upon the anodic oxidation conditions. As illustrated in Fig. 2A and Fig. 2C, the formation of the dense film structural region of the above metal oxide layer between the lower electrode 2 and the electron-emitting 15 bodies 6 in the pores results in forming a nonlinear device in the structure of metal / insulator / electron-emitting bodies (carbon), so as to impart the function of current limitation, which can prevent current fluctuation in discharge or the like on the 20 occasion of driving the electron-emitting device of the present invention and which can in turn prevent damage to the electron-emitting device. A specific production method of the above metal oxide layer will be described hereinafter, but it is first formed, for example, under 25 conditions for forming porous metal oxide and thereafter the thickness of the dense film structural region is adjusted in a widening step of described

hereinafter.

The structures of Fig. 2B and Fig. 2D do not have the metal oxide layer without the pores and the electron-emitting bodies (carbon) in the pores are electrically connected directly to the lower electrode. These structures are obtained by anodizing the lower electrode, thereafter sufficiently widening the pores by the widening step of pores hereinafter and thereafter the electron-emitting bodies (carbon) are formed in the pores, whereby the electron-emitting bodies are electrically connected to the lower electrode. In another method, the metal oxide layer without the pores between the lower electrode and the metal oxide layer with the pores is electrically broken by pulse voltage applied in the step of forming the electron-emitting bodies (carbon) in the pores of the anodic oxide layer described hereinafter, so that the electron-emitting bodies are electrically connected to the lower electrode. In the structures of Fig. 2B and Fig. 2D, the electron-emitting device is also provided with the nonlinear characteristics by tunneling between the electron-emitting bodies and the vacuum. The above "vacuum" is one equivalent to the vacuum ambience in which the substrate with the electron-emitting device formed thereon is set.

When the upper electrode 4 is present in the portions above the pores as in the structures of Fig.

2A and Fig. 2B, the electron-emitting bodies formed in the pores are in contact with the vacuum through the upper electrode. When the upper electrode 4 is absent in the portions above the pores on the other hand as in
5 the structures of Fig. 2C and Fig. 2D, the electron-emitting bodies formed in the pores are in direct contact with the vacuum.

With consideration to aspects of heat resistance of the electron-emitting device of the
10 present invention, stability of electron emission characteristics, improvement in repeatability, and so on, the carbon deposit for forming the electron-emitting bodies is preferably at least one of graphite, amorphous carbon and diamondlike carbon.

15 There are various methods for producing the above-stated electron-emitting device, among which an example is schematically illustrated in a step diagram of Fig. 3. A first production method for producing the structures of Fig. 2C and Fig. 2D will be described
20 below.

The first step is a step of forming the lower electrode of the metal or the semiconductor on the substrate. The substrate 1 is cleaned well with detergent, pure water, and organic solvent or the like,
25 a material for the lower electrode is deposited by vacuum evaporation, sputtering, or the like, and thereafter the lower electrode 2 is formed on the

substrate, for example, by the photolithography technology. The lower electrode may also be formed by plating.

The second step is a step of anodizing the lower electrode. An anodic oxidation system will be described herein using the conceptual drawing thereof illustrated in Fig. 4. In Fig. 4, numeral 1 represents a substrate, 31 an anodic oxidation tank, 32 an anodic oxidation electrolyte solution, 33 an electrode, 34 a power supply, and 35 an O-ring. The anodic oxidation electrolyte solution 32 for the metal such as Al is an aqueous solution of one selected from inorganic acids such as sulfuric acid, sulfamic acid, and phosphoric acid, and organic acids such as oxalic acid, malonic acid, and succinic acid, and a substance added thereto as solvent is polyhydric alcohol such as ethylene glycol, glycerin, or dextrin. On the other hand, the electrolyte solution for Si is an aqueous solution of HF. Further, an oxidation process such as thermal oxidation may be further added. The electrode 33 is the metal such as Pt. The anodic oxidation of the lower electrode is effected by energization from the power supply 34 with the electrode 33 as a cathode and the substrate 1 as an anode. The geometrical structure of the anodic oxide layer can be controlled by production conditions. Specifically, the spacing between the pores can be controlled by the anodic

oxidation voltage, the depths of the pores by the anodic oxidation time, and the diameters of the pores by such conditions as the composition of the electrolyte solution, the voltage, the current.

5 Further, control of the regular pores or the irregular pores can also be made by control of these conditions. Next, the substrate on which the anodic oxide layer was thus formed thereon is dipped in the anodic oxidation electrolyte solution or the like to adjust the diameter
10 of pores and thickness of the dense oxide film (this process will be called widening) and is washed well with water and thereafter dried in vacuum.

The third step is a step of forming the upper electrode on the metal or the semiconductor thus
15 anodized. The upper electrode is formed in the thickness of several nm to several ten nm on the above anodic oxide layer in the same manner as the lower electrode as described above.

The fourth step is a step of forming the
20 electron-emitting bodies in the pores of the anodic oxide layer. This step is a step of forming carbon in the pores of the aforementioned anodic oxide layer by applying the voltage to the upper electrode and lower electrode under existence of the organic material of a
25 gas state. The carbon formed in this step is graphite. The graphite herein is either of so-called HOPG, PG, and GC. HOPG indicates almost perfect graphite crystal

structure, PG somewhat disordered crystal structure having crystal grains of 20 nm or so, and GC more disordered crystal structure having crystal grains of 2 nm or so. In addition, the carbon herein may also be
5 non-crystalline carbon. The non-crystallin_carbon herein includes amorphous carbon and, a mixture of amorphous carbon with fine crystals of graphite.

Now, a vacuum process system used in the fourth step will be described referring to Fig. 5. In Fig. 5,
10 the same portions as those illustrated in Figs. 1A, 1B and 2A to 2D are denoted by the same reference numerals. In Fig. 5, numeral 55 indicates a vacuum vessel, 56 an exhaust pump, and 57 a supply of organic gas used in formation of carbon in the pores of the
15 anodic oxide layer of the electron-emitting device according to the present invention. The electron-emitting device of the present invention is placed in the vacuum vessel 55. Specifically, numeral 1 represents the substrate, 2 the lower electrode, 3 the
20 anodic oxide layer, and 4 the upper electrode. Further, numeral 51 denotes a power supply for applying the device voltage V_f to the electron-emitting device, 50 a current meter for measuring the device current I_f flowing in the lower electrode 2 and the upper
25 electrode 4, and 54 an anode electrode for capturing the emission current I_e of electrons emitted from the device. Numeral 53 designates a high voltage supply

for applying the voltage to the anode electrode 54, and
52 a current meter for measuring the emission current
I_e emitted from the electron-emitting device. As an
example, supposing the voltage of the anode electrode
5 is in the range of 0 to 10 kV, measurement can be
carried out while the distance H between the anode
electrode and the electron-emitting device is set in
the range of 10 μm to 8 mm. There is provided
equipment necessary for the measurement under a vacuum
10 ambience, such as a vacuum gage not illustrated, in the
vacuum vessel 55, so as to permit measurement and
evaluation under a desired vacuum ambience. The
exhaust pump 56 is composed of an ordinary high-vacuum
system consisting of a turbo pump or a rotary pump and
15 an ultrahigh vacuum system consisting of an ion pump or
the like. The whole of the vacuum process system shown
herein can be heated up to 350 °C by a heater not
illustrated.

The substrate 1 is set in the vacuum vessel and
20 the vacuum vessel is evacuated into a vacuum ambience.
Thereafter, the organic gas is introduced from the
supply of organic gas 57 into the vacuum vessel 55 and
the voltage is applied to the upper electrode and lower
electrode under the ambience containing the gas of
25 organic substance. The waveform of the voltage is a
waveform of pulses, which are repetitively applied. A
method for applying the voltage may be selected from a

method illustrated in Fig. 6A for continuously applying pulses with their pulse peak values of a constant voltage, and a method illustrated in Fig. 6B for applying voltage pulses with increasing pulse peak values.

In the method of the fixed application direction of the pulse voltage wherein either the upper electrode or the lower electrode is fixed at a higher potential while the other at a lower potential (Fig. 6A), supposing the upper electrode is fixed at the lower potential than the lower electrode, the carbon is formed mainly on the lower electrode side which is kept at the higher potential. In the method for applying the higher potential alternately to the upper electrode and to the lower electrode (Fig. 6B), the carbon is formed both on the upper electrode and on the lower electrode.

In Fig. 6A, T1 and T2 represent the pulse width and the pulse spacing of pulses in the voltage waveform. Normally, T1 is set in the range of 1 microsecond to 10 milliseconds and T2 in the range of 10 microseconds to 100 milliseconds. The peak values of the triangular waves are properly selected according to the form of the electron-emitting device. Under such conditions the voltage is applied, for example, for several minutes to several ten minutes. The pulse waves are not limited only to the triangular waves, but

desired waveforms may be employed including the rectangular waves. Further, T1 and T2 in Fig. 6B can be the same as those illustrated in Fig. 6A. The peak values of the triangular waves can be increased, for
5 example, by steps of about 0.1 V.

The preferred gas pressure of the organic substance for formation of the carbon differs depending upon the aforementioned application form, the shape of the vacuum vessel, the type of the organic substance,
10 and so on and is thus properly determined according to the circumstances. An appropriate organic substance can be selected from aliphatic hydrocarbons of alkane, alkene, and alkyne, aromatic hydrocarbons, alcohols, aldehydes, ketones, amines, organic acids such as
15 phenol, carboxylic acid, and sulfonic acid, and so on. Specific examples of such substances include saturated hydrocarbons represented by C_nH_{2n+2} such as methane, ethane, and propane, unsaturated hydrocarbons represented by the composition formula of C_nH_{2n} or the
20 like such as ethylene and propylene, benzene, toluene, methanol, ethanol, formaldehyde, acetaldehyde, acetone, methyl ethyl ketone, methylamine, ethylamine, phenol, formic acid, acetic acid, propionic acid, and so on. The organic gas is also selected according to the
25 diameter of the pores formed in the anodic oxide layer. This is because adsorption of the organic gas is also dependent on the diameter of the pores.

During this process carbon is deposited from the organic substance present in the ambience into the pores in the anodic oxide layer, whereby the device current I_f and emission current I_e change remarkably.

5 Completion of the fourth step is determined while measuring the device current I_f and the emission current I_e . The apertures of the upper electrode 4 above the pores, illustrated in Figs. 2C and 2D, are formed in the initial stage of application of the
10 above-stated voltage pulses in this step.

 The fifth step is a stabilization step. Namely, this step is a step of stabilizing the characteristics of the electron-emitting device produced by the first to the fourth steps. The fifth
15 step is a step of removing intermediate products of the organic material and also removing the organic gas, water, oxygen, etc. adsorbing to the substrate etc. from the carbon in the pores of the anodic oxide layer, whereby the step can impart to the device such a
20 property that the device current and the emission current monotonically increase above a certain threshold against the voltage applied to the device. This step is a step of exhausting the organic substance in the vacuum vessel and an evacuation apparatus for
25 evacuating the vacuum vessel is preferably one not using oil in order to avoid influence of the oil from the apparatus on the characteristics of the device.

Specifically, the evacuation apparatus can be selected from a sorption pump, an ion pump, and so on.

The partial pressure of the organic component in the evacuation apparatus is set to a partial pressure under which there is little carbon or carbon compound newly deposited, and is preferably not more than 1×10^{-8} Torr and particularly preferably not more than 1×10^{-10} Torr. It is further preferred that the whole of the vacuum apparatus be heated during evacuation of the inside of the vacuum apparatus so as to facilitate removal of molecules of the organic substance adsorbing to the inner wall of the vacuum apparatus and to the electron-emitting device. The heating condition at this time is desirably the temperature of 150 to 300 °C and the heating time of not less than several hours, but the heating condition is not limited particularly to this condition.

The ambience during driving after completion of the stabilization step is preferably maintained in the ambience at the end of the above stabilization operation, but it is not limited to this. Sufficient characteristics can be maintained by an ambience from which the organic substance is removed adequately but the vacuum degree of which is a little degraded. By employing such a vacuum ambience, deposition of new carbon substance can be suppressed, whereby the device current I_f and emission current I_e are stabilized as a

result.

Next, a second production method, which is a method for forming carbon or diamondlike carbon in a liquid, will be described referring to the step diagram of Fig. 3. The following describes an example for
5 producing the structures of Fig. 2A and Fig. 2B.

The first step is a step of forming the lower electrode of the metal or the semiconductor on the substrate, which is carried out in the same manner as
10 the method described in the first step of the first production method.

The second step is a step of anodizing the lower electrode, which is similar to the method described in the second step of the first production
15 step, but in which after the anodic oxidation, the substrate with the anodic oxide layer formed thereon is washed with water, dipped in the anodic electrolyte solution (that is "widening") and then is taken into the electrolytic tank of step 3.

20 The third step is a step of forming the electron-emitting bodies in the pores of the anodic oxide layer under existence of a liquid organic material. This step is a step of forming the electron-emitting bodies in the pores of the aforementioned
25 anodic oxide layer by applying the voltage to the electrode 33 and the lower electrode of Fig. 4. Using the same apparatus as illustrated in Fig. 4,

electrolysis is effected in an electrolyte solution of alcohol with the lower electrode as an anode and with the electrode 33 of Fig. 4 as a cathode, whereby diamondlike carbon can be deposited into the pores
5 formed by the anodic oxidation from the lower electrode side. The diamondlike carbon grows in a columnar shape in the pores with a lapse of the electrolytic time.

The fourth step is a step of forming the upper electrode on the metal or the semiconductor thus
10 anodized, in which the upper electrode is formed in the thickness of several nm to several ten nm over the above anodic oxide layer in the same manner as the aforementioned lower electrode was.

The fifth step is a stabilization step, which
15 is carried out in the same manner as the stabilization step described in the fifth step of the first production method.

[Example 1 of the first embodiment]

Fig. 7A is a plan view of a substrate on which
20 five electron-emitting devices of the present invention are placed and Fig. 7B is a schematic sectional view along 7B-7B of Fig. 7A.

In Figs. 7A and 7B, numeral 1 denotes a substrate, 73 anodic oxide layers, 71 lead wires of the
25 lower electrodes, 72 a lead wire of the upper electrodes, and 74 intersections between the lead wires 71 of the lower electrodes and the lead wire 72 of the

upper electrodes, at which the electron-emitting devices of the present invention are placed.

In the present example, substrates, each including five electron-emitting devices in either one of the structures of the four types illustrated in Figs. 2A, 2B, 2C, and 2D, will be called substrates A, B, C, and D, respectively.

A production method of the present example will be described specifically.

(Step 1: step of forming the lower electrode of metal on the substrate)

The substrate 1 of quartz glass was washed well with detergent, pure water, and organic solvent or the like, the material of Al for the lower electrode was deposited in the thickness of 200 nm by sputtering, and thereafter the lower electrode wires 71 were formed in a stripe pattern on the substrate 1 by the photolithography technology. The lower electrode wires 71 were covered in part by a known mask resin for plating in order to use parts of the lower lead wires 71 as terminals.

(Step 2: step of anodizing the lower electrodes)

Using the anodic oxidation system illustrated in Fig. 4, the lower electrodes of Al prepared in step 1 were anodized. For the substrates B and D, an aqueous solution of oxalic acid 30 g/l was used as an anodic oxidation electrolyte solution (32 in Fig. 4).

A Pt electrode was used as the electrode (33 in Fig. 4). The anodic oxidation was carried out at the constant voltage of 45 V from the power supply (34 in Fig. 4) with the electrode (33 in Fig. 4) as a cathode and the lower wires (71 in Figs. 7A and 7B) provided on the substrate 1, as anodes. On this occasion, the initial current density was 400 mA/cm², but it decreased with progress of anodic oxidation. Next, the substrate with the anodic oxide layers formed thereon was dipped in H₃PO₄ solution, washed well with water and thereafter dried in vacuum. The above anodic oxidation step resulted in forming the pores in the anodic oxide layers. For the substrates A and C, the anodic oxide layers with pores were formed under the same anodic oxidation conditions as in the case of the substrates B and D. A thickness of dense film is controlled by dipping in phosphoric acid solution in a shorter time than that of the cases of the substrates B and D. (Step 3: step of forming the upper electrode on the metal or the semiconductor thus anodized)

The upper electrode 72 was formed in the thickness of 10 nm on the above anodic oxide layers of each of the substrates A, B, C, and D in the same manner as the above lower electrodes had been formed. (Step 4: step of forming carbon in the pores of the anodic oxide layers (under existence of a gas organic material))

The substrate 1 was placed in the vacuum chamber also serving as a measuring device and the voltage was applied to the upper electrode and lower electrode under an ambience containing gas of acetone at 10^{-1} Pa. The voltage was applied for thirty minutes in the form of rectangular waves having the pulse width T1 of 1 ms and the pulse spacing T2 of 10 ms in the pulse waveform of Fig. 6A. At the same time, the current of device was monitored. The voltage was 10 V in the substrate A, B, C, or D. Apertures are formed in the upper electrode above the pores by the application of the above-stated voltage pulses in this step.

(Step 5: stabilization step)

Next, the acetone gas was exhausted well and thereafter the system was evacuated for ten hours while being heated at 250 °C.

(Step 6: step of again forming the upper electrode)

For the substrates A and B, the upper electrode was again formed in the same manner as above, thereby forming the structures of Figs. 2A and 2B.

[Comparative Example]

(Step 1) to (step 4) were carried out under the production conditions of substrate B, thereby separately preparing a substrate without execution of (step 5: stabilization step). This will be called substrate E.

[Results]

Then the substrate A, B, C, D, or E was set in the vacuum process system of Fig. 5, the voltage was applied to the lower electrode and upper electrode of each device, and to the anode electrode under an
5 ultrahigh vacuum, and the currents (the device current and emission current) and device voltage characteristics were measured. Figs. 8A and 8B show the current/voltage characteristics. At the same time, it was checked whether the voltage-controlled negative
10 resistance (VCNR characteristics) occurred with slowly sweeping the device voltage. Further, emission of electron beam was observed by emission of a fluorescent member placed at the anode. After the measurements, the samples thus formed were then observed with an
15 electron microscope, plane TEM, and so on.

As apparent from the current/voltage characteristics of Figs. 8A and 8B, the device current and emission current of the substrates A, B, C, and D demonstrate monotonically increasing characteristics
20 above their threshold. The current was negligible below the threshold (which will be called V_{th}). These verify that the devices are nonlinear devices demonstrating the nonlinear characteristics of the device current and emission current. On the other
25 hand, it is seen that the substrate E of the comparative example demonstrates the emission current of characteristics that are not the voltage-controlled

negative resistance characteristics (VCNR characteristics), but the device current of the voltage-controlled negative resistance characteristics (VCNR characteristics).

5 Since the substrates A and C have the structure of the dense anodic oxide layer / the anodic oxide layer having the pores, formed on the lower electrode, it is seen that this structure shifts V_{th} to the higher device voltage than that of the substrates B and D.

10 The diameter of the electron beam observed at the anode electrode was nearly equal to the overlapping part of the upper electrode with the lower electrode.

 When the devices were observed with the electron microscope, the regular pores as illustrated
15 in Fig. 1B were observed in the anodic oxide layer in either of the substrates. The diameter of the pores was 200 nm and the density of the pores was 3×10^8 pores/cm².

 The upper electrode exists above the pores in
20 the substrates A and B, whereas the upper electrode does not exist above the pores but does exist around the pores in the substrates C and D. This is because the upper electrode above the pores was removed in the case of the substrates C and D on the occasion of
25 applying the pulse voltage in the step of forming the electron-emitting bodies.

 Further, plane TEM samples were prepared and

observed, and it was verified that graphite-nature carbon existed in the pores in either sample. It seemed that more carbon was deposited in the pores in the substrate E. The deposit further contained carbon
5 other than graphite.

The present example substantiated the following. First, graphite-nature carbon can be formed in the pores of the anodized layer obtained by anodic oxidation of metal. Second, the devices obtained can
10 function as electron-emitting devices. Third, the stabilization step does not cause the voltage-controlled negative resistance characteristics (VCNR characteristics) and both the device current and emission current exhibit the monotonic increase
15 characteristics. Fourth, where the anodic oxide layer is the one having the dense anodic oxide layer functioning as an insulating layer and the anodic oxide layer having the pores, the current/voltage characteristics are shifted to the higher voltage side
20 of the device voltage. Fifth, the diameter of the electron beam observed at the anode electrode is nearly equal to the overlapping part of the upper electrode with the lower electrode and there is thus a little divergence of the beam.

25 [Example 2 of the first embodiment]

The present example is an example in which diamondlike carbon is formed in the pores of the

insulating layer, in liquid. A production method of the present example will be described specifically, again referring to Fig. 3.

(Step 1: step of forming the lower electrode)

5 A P-type Si wafer was used as a substrate. Here, the P-type wafer substrate functions as a lower electrode.

(Step 2: step of anodizing the lower electrode)

 Using the apparatus of Fig. 4, the anodic
10 oxidation operation was carried out in the aqueous solution of HF with the P-type Si wafer as an anode and Pt as a cathode (33 in Fig. 4), and thereafter the wafer was washed with water and then taken into the electrolytic tank of step 3.

15 (Step 3: step of forming the electron-emitting bodies in the pores of the anodic oxide layer (under existence of liquid organic material))

 This step is a step of forming carbon in the pores of the anodic oxide layer by applying the voltage
20 under existence of an organic material of a liquid state. Using the system similar to that of Fig. 4, electrolysis was carried out in the electrolyte solution of ethyl alcohol for one hour by applying the voltage between the anode of the lower electrode side
25 of device and the cathode Pt (the electrode 33 of Fig. 4). During the electrolysis the temperature of the solution was controlled at 60 °C by heating the

solution with an unrepresented heater. Then the substrate with the anodic oxide layer was washed well with water and thereafter dried in vacuum.

(Step 4: step of forming the upper electrode)

5 A Pt film was deposited as an upper electrode in the thickness of 10 nm by sputtering.

(Step 5: stabilization step)

The stabilization step was carried out in the same manner as in Example 1 above.

10 In the last stage, the above sample was set in the vacuum process system of Fig. 5, and the voltage was applied to the lower electrode and the upper electrode, and to the anode electrode to measure the currents (device currents and emission current) and the
15 device voltage characteristics in the same manner as in Example 1. At the same time, it was checked whether the voltage-controlled negative resistance characteristics (VCNR characteristics) appeared with slowly sweeping the device voltage. After the
20 measurements, the sample thus formed was observed with the electron microscope, the plane TEM, and so on.

The current/voltage characteristics of both the device current and emission current were the monotonically increasing characteristics over their
25 threshold and the current was negligible below the threshold, as in Example 1. These verified that the device was a nonlinear device demonstrating the

nonlinear characteristics of both the device current and emission current. The emission current was five times greater than those of the devices of Example 1. This is conceivably because of decrease of work
5 function of carbon in the pores or influence of shape.

In observation with the electron microscope, the holes of the porous structure were observed. Further, Raman and plane TEM samples were prepared and observed, and it was proved thereby that diamondlike
10 carbon existed in the holes.

[Example 3 of the first embodiment]

The present example is an example of application to an image pickup device in which a plurality of electron-emitting devices, which were
15 prepared by a method similar to that in Example 1, are placed in a two-dimensional array on a substrate. Fig. 9A and Fig. 9B are schematic views of the image pickup device of the present invention. Fig. 9A is a sectional view of an image pickup tube of the present
20 invention and Fig. 9B is a plan view of the substrate on which the electron-emitting devices are placed. In Figs. 9A and 9B, numeral 91 designates an electron-emitting device substrate (an electron source substrate), 92 lower electrodes (wires), 93 anodic
25 oxide layers, 94 upper electrodes (wires), 95 a photoconductive member, 96 a transparent electrode, 97 a photoconductive member substrate, 98 a device voltage

applying source, and 99 a power supply for applying the voltage to the photoconductive member. In Fig. 9A, the electron-emitting device substrate and the photoconductive member substrate are bonded to a support frame not illustrated, thereby composing a hermetically closed container. The inside of the container is maintained in a high vacuum. Although Fig. 9A is illustrated so that one of the upper electrodes is connected to the device voltage applying source, it is noted that all the upper electrodes are connected to the device voltage applying source.

Next described is the principle of the image pickup device of the present example. The operation of the image pickup device of the present example is similar to that of the conventional image pickup tubes, but the image pickup device of the present example is different from the conventional image pickup tubes in that an image is read using electron beams from the electron-emitting devices arrayed in the two-dimensional pattern and in that the image pickup device does not have a converging system for converging the electron beams. When light is incident to the photoconductive member 95, holes are created in the photoconductive member 95 by the incident light. The holes are accelerated toward the electron-emitting device substrate 91 by an electric field applied to the photoconductive member 95, so as to undergo avalanche

multiplication. On the other hand, electron beams emerge from the electron-emitting device substrate 91. Electrons are injected into the photoconductive member 95 in the number corresponding to the holes accumulated therein, and excessive electron beams return to the electron-emitting device substrate 91 to flow in the upper wires 94. In this way, signal current according to the holes generated in response to the incident light is outputted from a signal current amplifier.

Next, the structure of the image pickup device of the present example will be described. Over the electron-emitting device substrate 91, the anodic oxide layers 93 are formed in regions except for the lead portions of wires on the lower electrode wires 92, and the upper wires 94 are formed perpendicularly to the lower electrode wires 92. Intersecting portions between the lower electrode wires 92 and the upper wires 94 constitute the electron-emitting regions similar to those in Figs. 1A and 1B. The size of the electron-emitting device is 50 μm square. The photoconductive member 95 is made of Se and the thickness thereof is 4 μm . The separation between the electron-emitting device substrate 91 and the photoconductive member substrate 97 is 1 mm.

A method for producing the image pickup device of the present example will be described below. The side of electron-emitting device substrate 91 was

prepared in the same manner as in the example.

Further, the photoconductive member 95 was deposited by a resistance heating evaporation method of Se. The electron-emitting device substrate and the

5 photoconductive member substrate thus prepared were bonded to the unrepresented support frame. After the inside was evacuated through an exhaust pipe not illustrated, a hermetically closed container was formed. Then the image pickup device thus produced was
10 operated based on the principle of operation described previously and the signal current was obtained in 1:1 correspondence to the size of the electron-emitting devices. The operation was thus confirmed.

[Example 4 of the first embodiment]

15 The present example is an example of construction of a display device in which a plurality of electron-emitting devices, which were prepared in a method similar to that in Example 2, are placed in a two-dimensional array on a substrate. Figs. 10A and
20 10B are schematic views of the display device of the present invention. Fig. 10A is a schematic sectional view of the display device of the present invention and Fig. 10B is a plan view of the substrate on which the electron-emitting devices are placed. In Figs. 10A and
25 10B, numeral 100 represents a rear plate, 101 an electron-emitting device substrate (an electron source substrate), 102 lower electrodes (wires), 103 anodic

oxide layers, 104 upper electrodes (wires), 105 a metal back, 106 a fluorescent member, 107 a face plate, 108 a device voltage applying source, and 109 a high voltage supply for the anode. In Fig. 10A, the electron-emitting device substrate and the face plate are bonded to an unrepresented support frame to compose a hermetically closed container and the inside thereof is maintained in a high vacuum. Although Fig. 10A is illustrated so that one of the upper electrodes is connected to the device voltage applying source, it is noted that all the upper electrodes are connected to the device voltage applying source. The fluorescent member 106 is formed in a stripe pattern in which black stripes divide fluorescent materials of R (red), G (green), and B (blue) not illustrated, from each other.

Next described is the principle of the display device of the present example. In the display device of the present example, each electron-emitting device line in the two-dimensional array is selected by a scanning signal from the outside and electron beams are emitted from the devices in the electron-emitting device line selected with being modulated by a modulation signal from the outside. The electron beams emitted diverge a little in the electron-emitting devices of the present invention. Thus, the electron beams are accelerated without using a converging system of electron beam and are incident to the metal back/the

fluorescent member to cause luminescence. An image is displayed in this way.

The structure of the display device of the present example will be described below. Over the electron-emitting device substrate 101 the anodic oxide layers 103 are formed in regions except for the lead portions of wires on the lower electrode wires 102, and the upper wires 104 are formed perpendicularly to the lower electrode wires 102. Intersecting portions between the lower electrode wires 102 and the upper wires 104 constitute the electron-emitting devices similar to that in Figs. 1A and 1B. The display device was composed of $200 \times (160 \times 3)$ (i.e., R, G, and B) electron-emitting devices. Figs. 10A and 10B show those in part. The size of the electron-emitting device is $40 \mu\text{m}$ square. The fluorescent member 106 was high-acceleration fluorescent material P22 for CRT. The separation between the electron-emitting device substrate 101 and the face plate 107 was 2 mm. The voltage of 5 kV was applied to the metal back 105.

A method for producing the display device of the present example will be described below.

(Step 1: step of forming the lower electrodes of the metal or the semiconductor on the substrate 101)

The substrate was an n-type Si wafer. A plurality of stripes of P-type portions were formed in the n-type Si wafer. The stripes of the P-type

portions function as the lower electrodes.

(Step 2: step of anodizing the lower electrodes)

Using the apparatus of Fig. 4, the anodic
oxidation operation was carried out in the aqueous
5 solution of HF with the P-type portions of the Si wafer
as anodes and Pt as a cathode, and thereafter the wafer
was washed with water and then taken into the
electrolytic tank of step 3. The anodic oxide layers
were selectively formed in the stripes of the P-type
10 portions.

(Step 3: step of forming the electron-emitting bodies
in the pores of the anodic oxide layers (under
existence of organic material of liquid state))

This step is a step of forming the electron-
15 emitting bodies in the pores of the anodic oxide layers
by applying the voltage to the upper electrodes and
lower electrodes under existence of an organic material
of a liquid state. Using the apparatus similar to that
of Fig. 4, electrolysis was brought about in the
20 electrolyte solution of ethyl alcohol for one hour
between the cathode of the lower electrode side and the
anode. During the electrolysis the temperature of the
solution was controlled at 60 °C by heating the
solution by the heater not illustrated. Then the
25 substrate with the anodic oxide layers was washed well
with water and thereafter dried in vacuum.

(Step 4: step of forming the upper electrodes on the

metal or semiconductor thus anodized)

The upper electrodes were formed in the thickness of 10 nm by sputtering of Pt.

(Step 5: stabilization step)

5 The stabilization step was carried out in the same manner as in above Example 1.

 The fluorescent materials of R, G, and B were formed in stripes on the face plate 107 and after filming thereof, the metal back 105 was deposited by
10 evaporation. The electron-emitting device substrate 101 prepared as described above was placed on the rear plate 100 and the face plate 107 was bonded to the unrepresented support frame. After the inside was
15 evacuated through an exhaust pipe not illustrated, a hermetically closed container was constructed.

 Then the display device thus produced was operated based on the principle of operation described previously and it was verified that a bright image was displayed in high definition.

20 [Second Embodiment]

 Fig. 11A is a sectional view of the second embodiment. Fig. 11B is a partly enlarged, schematic view of part A in the sectional view of Fig. 11A. The present embodiment uses the anodic oxide layer for the
25 insulating layer. In Fig. 11A reference numerals are given in the similar fashion to those in Figs. 1A and 1B.

The substrate 1 to be employed herein can be selected from quartz glass, glass with a decreased content of impurity such as Na, soda lime glass, a glass substrate obtained by depositing SiO_2 on soda lime glass by sputtering or the like, ceramics such as alumina, an Si substrate, an Si substrate with a deposited layer of SiO_2 , and so on. Particularly, when the substrate 1 is a semiconductor substrate, a driver or the like for driving the electron-emitting device can also be mounted simultaneously.

The lower electrode 2 is selected from metals, such as Al, Ta, Nb, Ti, Zr, Hf, or Si, and semiconductors that can undergo anodic oxidation. The thickness of the lower electrode 2 is properly determined according to the thickness of the anodic oxide layer, the electrical resistance of the lower electrode, and so on. The materials for the lower electrode are not limited to only the metals that can be anodized, but they may also be of a stack form of a metal that cannot be anodized and a metal that can be anodized.

The anodic oxide layer 3 is formed by anodic oxidation of the lower electrode in part. In the anodic oxide layer 3 there exist regular or irregular pores 5. This will also be called porous structure in the present specification. The regular or irregular pores 5 can be formed by selecting anodic oxidation

conditions including a composition of an anodic
oxidation bath, the temperature of the bath, the
voltage, the time, etc., according to the material for
the lower electrode 2. Preferably, the regular pores
5 are selected. Diameters of the pores range from
several ten nm to several hundred nm and depths thereof
from several ten nm to several thousand nm. The
density of the pores is 10^8 to 10^{12} pores/cm². The shape
of the pores is not limited only to the circle, but the
10 ellipse, square, etc. can also be applied to the
electron-emitting devices of the present invention.
The variety of shapes can also be formed using the
focused ion beam or the like. Therefore, the
expression "length of pore" will also be used in place
15 of the diameter of pore in the present invention. In
each pore 5, carbon 6 electrically connected to the
lower electrode 2 is formed in a rim shape along the
inner wall of pore. Electrons are emitted from the
rim-shape part on the inner wall in each pore, thus
20 achieving linear electron emission from each pore
according to the shape of the pore.

The carbon may also be formed in the similar
fashion from the side of the upper electrode 4.

There is a gap created between the carbon
25 formed on the lower electrode 2, and the upper
electrode or, in the case where the carbon is also
formed from the side of the upper electrode 4, between

the carbon from the upper electrode 4 side and the carbon formed on the lower electrode 2. This gap is preferably several nm to several ten nm, and is properly determined according to the time of the step
5 of applying the voltage to the upper electrode and lower electrode under existence of the organic material detailed hereinafter, the voltage applied, and so on.

The upper electrode is formed above the anodic oxide layer and is made preferably of a material having
10 a high melting point, such as Pt, W, Mo, or Hf.

Structural examples of the above electron-emitting device of the present invention will be explained using the schematic sectional views of Figs. 12A to 12D. In Figs. 12A to 12D, the same portions as
15 those in Figs. 11A and 11B are denoted by the same reference numerals. In the figures reference numeral 7 designates an electroconductive member of metal or the like and 8 a small gap between the upper electrode and the electron-emitting bodies. There are four kinds of
20 structures illustrated in Figs. 12A to 12D, but other structures may also be employed, without having to be limited to these illustrated structures. The following describes examples using the metal for the upper
25 electrode and the lower electrode, but they may also be made of the semiconductor.

The structure of Fig. 12A is metal (lower electrode) / metal oxide layer / pores, each having a

rim-shape electron-emitting body 6 along the inner wall of pore / vacuum / metal (upper electrode) 4 formed in the regions except for the regions above the pores.

The structure of Fig. 12B is metal (lower electrode) / pores, each having a rim-shape electron-emitting body 6 along the inner wall of pore / vacuum / metal (upper electrode) 4 formed in the regions except for the regions above the pores. The structure of Fig. 12C is metal (lower electrode) / metal oxide layer / pores,

each having a pole-shaped electroconductive member 7 and a rim-shape electron-emitting body 6 along the inner wall of pore / vacuum / metal (upper electrode) 4 formed in the regions except for the regions above the pores. The structure of Fig. 12D is metal (lower electrode) / pores, each having a pole-shaped electroconductive member 7 and a rim-shape electron-emitting body 6 along the inner wall of pore / vacuum / metal (upper electrode) 4 formed in the regions except for the regions above the pores.

In the structures of Fig. 12A and Fig. 12C, the metal oxide layer 3 is obtained on the occasion of anodic oxidation of the lower electrode, and two structural regions, a dense film structural region without pores and a film structural region with pores, can be obtained in this metal oxide layer 3, depending upon the anodic oxidation conditions. As illustrated in Fig. 12A and Fig. 12C, the formation of the dense

film structural region of the above metal oxide layer
between the lower electrode 2 and the electron-emitting
bodies 6 in the pores results in forming a nonlinear
device in the structure of metal / insulator / rim-
5 shape electron-emitting bodies, so as to impart the
function of current limitation, which can prevent
current fluctuation in discharge or the like on the
occasion of driving the electron-emitting device of the
present invention and which can in turn prevent damage
10 to the electron-emitting device. A specific production
method of the above metal oxide layer will be described
hereinafter, but it is first formed, for example, under
conditions for forming the porous metal oxide and
thereafter the thickness of the dense film structural
15 region is adjusted in a widening step of pores
described hereinafter.

The structures of Fig. 12B and Fig. 12D do not
have the metal oxide layer without the pores and the
electron-emitting bodies (carbon) in the pores are
20 electrically connected directly to the lower electrode.
This structure is constructed by anodizing the lower
electrode, thereafter sufficiently widening the pores
by the widening step of pores described hereinafter,
and further forming the electron-emitting bodies
25 (carbon) in the pores, whereby the lower electrode
becomes electrically connected to the electron-emitting
bodies. On this occasion, the metal oxide layer

without the pores between the lower electrode and the metal oxide layer with the pores may be electrically broken by the pulse voltage applied in the step of forming the carbon in the pores of the anodic oxide layer described hereinafter, so that the electron-emitting bodies are electrically connected to the lower electrode in some cases.

In the structures of Fig. 12B and Fig. 12D, the electron-emitting device is also provided with the nonlinear characteristics by tunneling between the electron-emitting bodies and the vacuum. In the structures of Fig. 12C and Fig. 12D, there are the pole-shaped electroconductive bodies and the rim-shaped electron-emitting bodies along the inner walls of pores, in the pores. In these cases, the conductive bodies decrease the resistance of the region from the lower electrode to the electron-emitting bodies, so that the insulating layer can be formed in larger thickness, so as to decrease the capacitance between the lower electrode and the upper electrode, which is advantageous in terms of driving.

The electrical connection with the lower electrode can also be achieved in such a way that the metal is precipitated by alternating current into the pores of the anodic oxide film by the coloring method of the anodic oxide film conventionally well known whereupon the precipitating metal into the pores

migrates into the dense anodic oxide film to implement the electrical connection. The above "vacuum" is one equivalent to the vacuum ambience in which the substrate with the electron-emitting device formed thereon is set.

In the electron-emitting device of the present invention described above, the carbon making the electron-emitting bodies is preferably at least one of graphite, amorphous carbon, and diamondlike carbon, particularly, in terms of heat resistance, stability of electron emission characteristics, and improvement in repeatability, as stated previously.

Next described is an electron-emitting mechanism of the electron-emitting device of the present invention in the structural examples of Figs. 12A to 12D. In the surface conduction electron-emitting device stated previously in the related background art, according to Japanese Laid-open Patent Application No. 9-82214, electrons are once emitted into the vacuum outside the anode from a certain position on the anode side (which is also called the higher potential side) of the fissure region, in the fissure region of the surface conduction electron-emitting device. The electrons once emitted move in the electric field created by the cathode (which is also called the lower potential side) and the anode, and electrons flying over the singular point

(hereinafter referred to as a stagnation point) of the electric field are attracted to the anode plate by the electric field created by the voltage applied thereto. The electrons that do not reach the singular point of the electric field drop onto the anode, and some of electrons are scattered here to be deflected and again emitted into the vacuum. Electrons moving over the singular point of the electric field as a result of repetition of this scattering also reach the anode plate.

It is described in the prior art application that, in order to largely increase the electron emission efficiency, the electric field needs to be set in such conditions that most of the electrons once emitted are attracted to the anode plate without dropping onto the anode in the above mechanism of electron emission and that the electron emission efficiency can be increased by providing the field correcting electrode outside the device electrode and applying a sufficiently higher voltage thereto than the voltage applied to the device for emission of electron.

In contrast with it, in the case of the electron-emitting device of the present invention, when the higher potential is applied to the upper electrode and the lower potential than that to the upper electrode is applied to the lower electrode, a potential difference between them is placed in the

small gap between the upper electrode 4 and the electron-emitting bodies 6, whereupon electrons are emitted from the electron-emitting bodies into the vacuum. Since a strong electric field is placed in the small gap corresponding to the fissure of the
5 aforementioned prior art, the electrons emitted from the electron-emitting bodies 6 into the vacuum collide with the upper electrode 4 to be scattered, just as in the case of the surface conduction electron-emitting
10 device described previously in the related background art. It is, however, assumed that, in the case of the electron-emitting device of the present invention, the electrons reach the anode plate over the singular point of the electric field without repetition of scattering.

15 Fig. 13 is a diagram to show the principle of the electron-emitting device of the present invention. Fig. 13 is a schematic sectional view of Fig. 12D. In Fig. 13 the portions denoted by the same reference numerals as those in Fig. 12D indicate the same
20 portions. In the figure, h indicates the distance between the electron-emitting device and the anode plate, d the length of pore, and V_a the potential of the anode plate.

25 The following discussion is made with focusing attention on electrons emitted from the electron-emitting body 6 on one side. The electrons emitted from the electron-emitting body 6 into the vacuum

collide with the upper electrode 4 because of the electric field placed in the small gap to be first scattered isotropically. Since the strong electric field from the upper electrode 34 present at the very close distance considerably decreases the stagnation point described above, as compared with that in the conventional surface conduction electron-emitting device, the electrons isotropically scattered reach the anode plate without repetitive scattering, mostly after scattered only once. On the other hand, where the thickness of the upper electrode 4 is small, the electrons also reach the anode plate, mostly after scattered only once, without repetitive scattering. It is considered that the above accounts for the increase of the electron emission efficiency.

An important factor for the effect of the electric field of the upper electrode opposite to the upper electrode 4 is the diameter of the aperture. Supposing the work function of the conductive electron-emitting body is 4 to 5.5 eV, the electric field for emission of electrons into the small gap is not less than 10^7 V/cm. When the stagnation point being the singular point of the electric field as defined in the aforementioned prior art is applied to the prior art electron-emitting device and the present invention, the distance X_s of the stagnation point without 34 is represented by the following equation.

$$X_s = h \cdot V_f / (\pi \cdot V_a)$$

On the other hand, the stagnation point X_s' with 34 is indicated by the following equation.

$$X_s' = h \cdot V_f / \{ \pi \cdot V_a + h \cdot V_f / (\pi \cdot d) \}$$

5 Therefore, the smaller the diameter of the aperture, the more the stagnation point is constricted. Particularly, from the reason that the constriction effect of the stagnation point can be expected even at the upper electrode voltage of several ten V, the
10 diameter of the aperture is preferably not more than 0.5 μm and more preferably not more than 0.2 μm . Further, since the conductive electron-emitting body is present along the inner wall of pore, the wall in the pore is kept at one potential, which further constricts
15 the aforementioned stagnation point. This further increases the electron emission efficiency.

The effect of the formation of the rim-shape electron-emitting body on the electron emission efficiency can be expected before the depth of the pore
20 indicating the same potential becomes nearly equal to the diameter of the pore.

Further, the thickness of the upper electrode is preferably as thin as possible in order to suppress the repetitive scattering and, from examples, the
25 thickness is preferably not more than 0.2 μm in terms of the efficiency. For specifying the condition by the thickness of the upper electrode, the small gap

contributing to the emission of electrons has to be present at the edge of the upper electrode. From the viewpoint of suppressing the repetitive scattering, it corresponds to the distance from the small gap to the upper surface of the upper electrode.

The driving voltage is a low driving voltage, because the gap is small. Since the direction of the voltage to draw the electrons is coincident with the direction toward the anode plate, a spread of the electron beam, though scattered isotropically, is suppressed relatively.

There are a variety of methods for producing the electron-emitting device described above, among which an example will be described referring to the step diagram of Fig. 14.

(Step 1) Step of forming the lower electrode of the metal or the semiconductor on the substrate

The substrate 1 is cleaned well with detergent, pure water, and organic solvent or the like, the material for the lower electrode is deposited by vacuum evaporation, sputtering, or the like, and thereafter the lower electrode 2 is formed on the substrate, for example, by the photolithography technology. The lower electrode may also be formed by electrolytic crystallization.

(Step 2) Step of anodizing the lower electrode
An anodic oxidation system will be first

described herein using the conceptual drawing thereof illustrated in Fig. 15. Numeral 51 denotes an anodic oxidation tank, 52 an anodic oxidation electrolyte solution, 53 an electrode, 54 an anodic oxidation power supply, 55 a temperature controller for controlling the temperature of the anodic oxidation electrolyte solution 52, 56 a vessel for water circulating in the temperature controller, and 57 the circulating water for control of temperature.

10 The anodic oxidation electrolyte solution 52 for the metal such as Al is an aqueous solution of one selected from inorganic acids such as sulfuric acid, sulfamic acid, and phosphoric acid, and organic acids such as oxalic acid, malonic acid, and succinic acid, 15 and the substance added thereto as solvent is polyhydric alcohol such as ethylene glycol, glycerin, or dextrin. On the other hand, the electrolyte solution for Si is an aqueous solution of HF. Further, an oxidation process such as thermal oxidation may be 20 further added.

 The electrode 53 is the metal such as Pt. The anodic oxidation of the lower electrode is effected by energization from the power supply 54 with the electrode 53 as a cathode and the substrate 1 with the 25 lower electrode formed thereon, as an anode. The geometrical structure of the anodic oxide layer can be controlled by production conditions. Specifically, the

spacing between the pores can be controlled by the anodic oxidation voltage, the depths of the pores by the anodic oxidation time, and the diameters of the pores by such conditions as the composition of the electrolyte solution, the voltage, the current.

Further, control of the regular pores or the irregular pores can also be made by control of these conditions.

Next, the substrate with the anodic oxide layer formed thereon is dipped in the anodic oxidation electrolyte solution or the like to adjust the diameter of the pores and the thickness of the dense oxide film. (This step will be called widening.) Then the substrate is washed well with water and then dried in vacuum.

(Step 3) Step of forming the upper electrode on the metal or the semiconductor thus anodized

The upper electrode is formed in the thickness of not more than 200 nm in the same manner as the lower electrode was.

(Step 4) Step of forming the electron-emitting bodies in the pores of the anodic oxide layer (under existence of organic material of gas state)

This step is a step of forming carbon in the pores of the aforementioned anodic oxide layer by applying the voltage to the upper electrode and lower electrode under existence of the organic material of a gas state. The carbon formed in this step is, for

example, graphite (including so-called HOPG, PG, and GC). HOPG indicates the almost perfect graphite crystal structure, PG somewhat disordered crystal structure having crystal grains of 20 nm or so, and GC more disordered crystal structure having the crystal grains of 2 nm or so. In addition, the carbon herein may also be non-crystalline carbon (which means amorphous carbon and, a mixture of amorphous carbon with fine crystals of the aforementioned graphite).

10 [Example 1 of the second embodiment]

The electron-emitting devices were produced in the same structure as in Figs. 7A and 7B.

Production steps of the present example will be described specifically referring to Fig. 14.

15 (Step 1: step of forming the lower electrodes of metal on substrate)

The substrate 1 was prepared by depositing SiO_2 in the thickness of 1 μm on soda lime glass and the substrate 1 was washed well with detergent, pure water, and organic solvent or the like. Then the material of Al for the lower electrodes was deposited in the thickness of 500 nm on the substrate by sputtering and thereafter the lower electrode wires 71 were formed in stripes on the substrate 1 by the photolithography technology. For using parts of the lower lead wires 71 as terminals, they were covered with a known mask resin for plating.

20

25

(Step 2: step of anodizing the lower electrodes)

Using the apparatus of Fig. 15, the anodic oxidation was carried out to anodize parts of the Al lower electrodes prepared in (step 1). The anodic oxidation electrolyte solution 52 was an aqueous solution of oxalic acid 30 g/l. The electrode 53 was the Pt electrode. The anodic oxidation was carried on at 5 °C for five minutes by the constant voltage of 40 V from the power supply 55 with the cathode of the electrode 53 and the anode of the lower wires 71 provided on the substrate 1. On this occasion, the initial current density was 300 mA/cm², but the current density decreased with progress of the anodic oxidation and thereafter increased once to be saturated. Then the substrate with the anodic oxide layers was immersed in an aqueous solution of phosphoric acid for thirty minutes to remove the dense anodic oxide layer and thereafter washed well with water.

(Step 3: step of forming columnar metal in the pores of the anodic oxide layers)

Formation of the columnar metal in the pores was carried out using the system of Fig. 16.

In Fig. 16, portions with the same reference numerals as those in Fig. 15 indicate like portions. Numeral 91 represents a counter electrode for electrolytic deposition of metal, which is a counter electrode made of an inactive electrode such as carbon

or Pt or the same material as the electrodeposited metal. Numeral 92 indicates a container for a metal electrodeposition liquid, 93 a power supply for electrodeposition, and 94 an electrodeposition solution
5 containing the metal.

In this step Ni was electrodeposited by the constant current at the current density of 1 mA/cm^2 , using the Pt electrode as the counter electrode 91 and 5 % NiSO_4 and 4 % H_3BO_3 as the electrodeposition
10 solution 94 containing the metal. An electrodeposition amount of columnar Ni was controlled by time and the columnar Ni was formed in each pore. The electrodeposition time was 100 seconds.

(Step 4: step of forming the upper electrode on the
15 metal or the semiconductor thus anodized)

The upper electrode 82 was formed in the thickness of 10 nm in the same manner as the lower electrodes were.

(Step 5: step of forming carbon in the pores of the
20 anodic oxide layers (under existence of organic material of gas state))

The substrate 1 was set in the vacuum chamber also serving as a measuring device and the voltage was applied to the upper electrode and lower electrodes
25 under an ambience containing gas of benzonitrile at 10^{-4} Pa. In step 5, three devices out of the five devices were processed by applying the rectangular waves of the

voltage waveform having the pulse width T1 of 1 ms and the pulse spacing T2 of 10 ms in the pulse waveform of Fig. 6A with the lower electrode side at the higher potential for twenty minutes. After that, the upper
5 electrode side was kept at the higher potential and the voltage was applied for 20 minutes. Further, the current of the devices was monitored at the same time. The voltage was 17 V. The two remaining devices out of the five devices were processed similarly by applying
10 the voltage of 17 V in the pulse waveform of Fig. 6B for 20 minutes.

(Step 6: stabilization step)

Then the benzonitrile gas was exhausted sufficiently and thereafter the system was evacuated
15 for two hours while being heated at 300 °C.

Then the substrate was set in the vacuum process system of Fig. 5 and the voltage was applied to the lower electrode and upper electrode of each device, and to the anode electrode to measure the currents (the
20 device current and emission current) and the device voltage characteristics. Further, electron beams were observed by luminescence of the fluorescent member placed at the anode. After the measurements, the sample thus formed was then observed with the electron
25 microscope, TEM, and so on.

The device current and emission current both of each device demonstrated the monotonically increasing

characteristics over their threshold. The current was negligible below the threshold (called V_{th}). Values of emission current of the devices obtained with application of the pulses of Fig. 6A were equivalent to those of the devices obtained with application of the pulses of Fig. 6B and, therefore, their emission efficiencies were also equivalent.

In observation with the electron emission, the regular pores were observed in the anodic oxide layers. The density of the pores was 1×10^9 pores/cm².

Further, cross-sectional samples were prepared and the inside of the pores was observed. The cross sections of the devices were as illustrated in Fig. 17A and Fig. 17B. In Figs. 17A and 17B, the same reference symbols as those in Figs. 12A to 12D denote like portions. Fig. 17A is a cross section of the devices in which carbon was formed by applying the pulses of Fig. 6A in step 5, while Fig. 17B is a cross section of the devices in which carbon was formed by applying the pulses of Fig. 6B in step 5. Numeral 111 indicates the carbon formed on the upper electrode side.

As illustrated in Fig. 17A, where the carbon was formed with application of the pulses of Fig. 6A, the Ni metal was deposited in the columnar shape 110 nm high in the pores from the lower electrode 2 of Al and rim-shape amorphous carbon was further formed along the inner walls of the pores on the top surface of columnar

Ni. Further, amorphous carbon was also formed similarly on the side of the upper electrode 4. A small gap was formed between the carbon on the upper electrode 4 side and the carbon on the lower electrode 2 side and the gap was formed at the edge of the upper electrode. The gap was several nm. The thickness of the anodic oxide film was 150 nm.

On the other hand, where the carbon was formed with application of the pulses of Fig. 6B, as illustrated in Fig. 17B, the Ni metal was deposited in the columnar shape in the pores on the lower electrode 2 of Al and rim-shape amorphous carbon was further formed along the inner walls of the pores on the top surface of columnar Ni. Further, amorphous carbon was also formed similarly on the side of the upper electrode 4. The carbon was formed to the position 20 nm apart from the bottom surface of the upper electrode and a small gap was formed between the two carbon layers. The gap was several nm.

The above proved the following. First, the rim-shape carbon is formed along the inner walls of the pores, because the deposition rate is controlled under the low partial pressure on the top surface of the columnar metal layer formed in the pores of the anodic oxide layer which is obtained by anodic oxidation of the metal. Second, the small gap of several nm is formed between the carbon films on the upper electrode

side and on the lower electrode side. Third, the emission current and electron emission efficiency are equivalent as long as the small gap is located in the range of 20 nm from the bottom surface of the upper electrode. Since the distance from the gap to the top surface of the upper electrode is 30 nm including the thickness of the upper electrode in the both examples, the probability is assumed to be low of loss of the electrons emitted from the lower electrode side, in the pores. Fourth, the stabilization step enables the device current and emission current to demonstrate the monotonically increasing characteristics without occurrence of the voltage-controlled negative resistance characteristics, or the VCNR characteristics.

[Example 2 of the second embodiment]

In the present example the substrate was constructed in the device layout similar to Example 1 of the second embodiment. The upper electrode was formed in a variety of thicknesses and influence thereof was investigated. Step 1 to step 3, and step 6 were carried out in the same manner as in Example 1. The description of step 1 to step 3, and step 6 will be omitted herein and only steps 4 and 5 will be described in detail.

(Step 1: step of forming the lower electrodes of metal on the substrate)

This step was carried out in the same manner as step 1 of Example 1.

(Step 2: step of anodizing the lower electrodes)

5 This step was carried out in the same manner as step 2 of Example 1.

(Step 3: step of forming columnar metal in the pores of the anodic oxide layers)

This step was carried out in the same manner as step 3 of Example 1.

10 (Step 4: step of forming the upper electrode on the metal or the semiconductor thus anodized)

The upper electrode 72 was formed in either of four thicknesses of 5, 10, 100, and 500 nm on each substrate in the same manner as the lower electrodes,
15 thus forming four substrates.

(Step 5: step of forming carbon in the pores of the anodic oxide layers (under existence of organic material of gas shape))

Each substrate 1 was set in the vacuum chamber
20 also serving as a measuring device and the voltage was applied to the upper electrode and lower electrode under an ambience containing gas of benzonitrile at 10^{-4} Pa. Three devices out of the five devices were processed by applying the rectangular waves of the
25 voltage waveform having the pulse width T1 of 1 ms and the pulse spacing T2 of 10 ms in the pulse waveform of Fig. 6A for fifteen minutes with the lower electrode

side at the higher potential. After that, the upper electrode was kept at the higher potential and the voltage was applied for five minutes. At the same time, the current of device was monitored. The voltage
5 was 15 V.

(Step 6: stabilization step)

This step was carried out in the same manner as step 2 of Example 1.

Next, each substrate was set in the vacuum
10 process system of Fig. 5 and the voltage was applied to the lower electrode and upper electrode of each device, and to the anode electrode to measure the currents (the device current and emission current) and the device
15 voltage characteristics. Further, the electron beam was observed by luminescence of the fluorescent member placed at the anode.

Fig. 18 shows the relation between thickness of the upper electrode and emission efficiency. As shown in Fig. 18, the electron emission efficiency did not
20 decrease below the thickness of about 200 nm and then decreased with increasing thickness of the upper electrode over 200 nm. The electron emission efficiency is defined as a ratio of emission current to device current. Further, the beam size also decreased.

25 In observation of the form of the upper electrode, particularly, in the case of the upper electrode having the large thickness, where the

thickness was greater than the diameter of the pores,
the inside of the pores was also covered in part. When
the small gap was observed with section TEM, the small
gap was formed at the edge of the bottom surface of the
5 upper electrode in either sample, as in Example 1.

The above verified the following. First, the
small gap is formed at the edge of the upper electrode,
irrespective of the thickness of the upper electrode.
Second, the emission current and electron emission
10 efficiency decrease, depending upon the thickness of
the upper electrode. This is assumed to be due to the
high probability of loss at the upper electrode of the
porous shape, of the electrons emitted from the lower
electrode side.

15 [Example 3 of the second embodiment]

In the present example the substrate was
constructed in the device layout similar to Example 1
of the second embodiment. In the present example, SiO_2
was used as the insulating layer instead of the anodic
20 oxide layer of aluminum in Example 1. Production steps
of the present example will be described specifically.
(Step 1: step of forming the lower electrodes of metal
on the substrate)

The substrate 1 was prepared by depositing SiO_2
25 in the thickness of 1 μm on soda lime glass and then
the substrate 1 was washed well with detergent, pure
water, and organic solvent or the like. The material

Pt for the lower electrode was deposited in the thickness of 500 nm on the substrate by sputtering and thereafter the lower electrode wires 71 were formed in stripes on the substrate 1 by the photolithography technology.

(Step 2: step of forming the insulating layer)

Next, SiO_2 was deposited in the thickness of 50 nm by sputtering.

(Step 3: step of forming the upper electrode on the insulating layer)

The upper electrode 72 was made of Pt in the thickness of 10 nm in the same manner as the lower electrodes were.

(Step 4: step of forming the pores in the insulating layer)

In the stack structure of lower electrode / SiO_2 / upper electrode as described above, four types of pores were formed as follows by the focused ion beam method; (the diameter 50 nm and the pitch 100 nm of the pores), (the diameter 200 nm and the pitch 400 nm of the pores), (the diameter 500 nm and the pitch 1000 nm of the pores), and (the diameter 1000 nm and the pitch 2000 nm of the pores). Here, the pitch is a distance between centers of adjacent pores.

(Step 5: step of forming carbon in the pores of the insulating layer (under existence of organic material of gas shape))

The substrate 1 was set in the vacuum chamber also serving as a measuring device and the voltage was applied to the upper electrode and lower electrode under an ambience containing gas of benzonitrile at 10^{-4} Pa. The rectangular waves of the voltage waveform having the pulse width T1 of 1 ms and the pulse spacing T2 of 10 ms in the pulse waveform of Fig. 6A were applied for fifteen minutes and then the lower electrode side was kept at the higher potential for five minutes.

(Step 6: stabilization step)

Then the benzonitrile gas was exhausted sufficiently and thereafter the system was evacuated for two hours while being heated at 300 °C.

Then the substrate was set in the vacuum process system of Fig. 5 and the voltage was applied to the lower electrode and upper electrode of each device, and to the anode electrode to measure the currents (the device current and emission current), and the device voltage characteristics.

The electron emission efficiency was dependent upon the diameter of the pores as illustrated in Fig. 19, and the electron emission efficiency increased with decreasing diameter of pore.

[Example 4 of the second embodiment]

The present example is an example of application to the image pickup device of Figs. 9A and

9B described previously, in which a plurality of electron-emitting devices prepared by the same method as in Example 1 of the second embodiment are placed in a two-dimensional array on the substrate.

5 The production method of the image pickup device of the present example is the same as in the first embodiment. The image pickup device produced in this way was operated based on the principle of operation stated previously, whereupon the signal
10 current was obtained in 1:1 correspondence to the size of the electron-emitting device, thereby verifying the operation.

[Example 5 of the second embodiment]

 The present example is an example of
15 construction of the display device of Figs. 10A and 10B described previously, in which a plurality of electron-emitting devices produced by the same method as in Example 1 of the second embodiment are arrayed in a two-dimensional pattern on the substrate. The
20 production method of the display device of the present example is the same as in the first embodiment. The display device produced in this way was operated based on the principle of operation discussed previously, and a bright image was displayed in high definition.

25 [Third Embodiment]

 Fig. 20A is a sectional view of the electron-emitting device of the present embodiment. Fig. 20B is

a partly enlarged, schematic view of part A in the sectional view of Fig. 20A. The present embodiment is application of the anodic oxide layer to the insulating layer. Figs. 21A to 21D illustrate respective
5 electron-emitting devices having a variety of electron-emitting bodies. Figs. 22A and 22B show other structural examples.

In Figs. 20A and 20B and Figs. 21A to 21D, numeral 1 denotes a substrate, 2 an upper electrode, 3
10 an anodic oxide layer, 4 an upper electrode, 5 pores of the porous structure, 6 electron-emitting bodies, and 207 a small gap.

The substrate 1 to be employed herein can be selected from quartz glass, glass with a decreased
15 content of impurity such as Na, soda lime glass, a glass substrate obtained by depositing SiO_2 on soda lime glass by sputtering or the like, ceramics such as alumina, an Si substrate, an Si substrate with a deposited layer of SiO_2 , and so on. Particularly, when
20 the substrate 1 is a semiconductor substrate, a driver or the like for driving the electron-emitting device can also be mounted simultaneously.

The lower electrode 2 is selected from metals, such as Al, Ta, Nb, Ti, Zr, Hf, or Si, and
25 semiconductors that can undergo anodic oxidation. The thickness of the lower electrode 2 is properly determined according to the thickness of the anodic

oxide layer, the electrical resistance of the lower electrode, and so on. The materials for the lower electrode are not limited to only the metals that can be anodized, but they may also be of a stack form of a metal that cannot be anodized and a metal that can be anodized.

The anodic oxide layer 3 is formed by anodic oxidation of the lower electrode in part. In the anodic oxide layer 3 there exist regular or irregular pores 5. This will also be called porous structure in the present specification. The regular or irregular pores 5 can be formed by selecting anodic oxidation conditions including a composition of an anodic oxidation bath, the temperature of the bath, the voltage, the time, etc., according to the material for the lower electrode 2. Preferably, the regular pores are selected. Diameters of the pores range from several ten nm to several hundred nm and depths thereof from several ten nm to several thousand nm. The density of the pores is 10^8 to 10^{12} pores/cm². The shape of the pores is not limited only to the circle, but the ellipse, square, etc. can also be applied to the electron-emitting devices of the present invention. The variety of shapes can also be formed using the focused ion beam or the like. Therefore, the expression "length of pore" will also be used in place of the diameter of pore in the present invention. Each

pore 5 has carbon of an electron-emitting body 6 electrically connected to the lower electrode 2.

The electron-emitting bodies can be formed in a variety of forms. The upper electrode 4 is kept at the higher potential than the lower electrode 2 is, so as to create a locally high electric field in the electron-emitting bodies, thereby causing electrons to tunnel from the electron-emitting bodies into the vacuum. The above "vacuum" is equivalent to the vacuum ambience in which the substrate with the electron-emitting device formed is set.

Fig. 21A is an example in which needlelike electrodes are provided in the pores. The needlelike electrodes are equivalent to those called the Spindt type stated previously.

Fig. 21B is an example in which small particles are provided in the pores. Grains of the small particles correspond to the tips of the needlelike electrodes of Fig. 21A.

Since in the electron-emitting bodies of Figs. 21A and 21B the local electric field is strong and the thickness of the vacuum part is large, the capacitance can be relatively lower than in the structures of Figs. 21C and 21D described below.

Fig. 21C is an example in which a high electric field is created in a small gap 207 between a rim-shape conductive body formed along the inner wall of each

pore and the upper electrode to emit electrons. Since the electron-emitting bodies are formed in the rim shape or the linear shape along the inner walls of the pores, the area capable of emitting electrons can be increased considerably, as compared with the structure of Fig. 21A, so that large electron emission current can be obtained.

Fig. 21D is an example in which the electron-emitting bodies 6 are conductive bodies of the columnar shape formed in the pores and in which a high electric field is created in a small gap 207 between the columnar conductive bodies 6 and the upper electrode to emit electrons. Since the electron-emitting bodies are of the rim shape or the linear shape along the inner walls of the pores, the area capable of emitting electrons can be increased considerably, as compared with the structure of Fig. 21A, so that large electron emission current can be obtained.

The upper electrode is formed on the anodic oxide layer, and the electron-transmitting portions above the pores are preferably made of a conductive material with excellent electron transmission characteristics and heat resistance and particularly preferably made of carbon or the like. Here, the "carbon" means a carbon material having at least one of graphite, amorphous carbon, and diamondlike carbon.

In order that the upper electrode can cover the

apertures of the pores, the thickness of the upper electrode is set to be not less than $0.5 \times L$ where L is the length of the pores.

Letting λ stand for the mean free path of
5 transmission of electrons, the thickness of the upper electrode is not more than 2λ for efficient transmission. In general, electron transmittance T is expressed by the following.

$$T = A \exp (-t/\lambda)$$

10 In the above equation, A represents a constant and t the thickness of the upper electrode. From the above equation, the transmittance of not less than 10 % of injected electrons can be expected if the thickness of the upper electrode is not more than 2λ . In the above
15 equation, the mean free path λ can be calculated from dependence of emission current on the thickness of the upper electrode.

For example, in the case of the carbon, which is the particularly preferred material in the present
20 invention, the above requirements simultaneously determine preferred ranges for the thickness of the upper electrode and for the length of the pores; for example, when the thickness of the upper electrode is 50 nm, the length of the pores is not more than 100 nm.

25 The thickness of the upper electrode on the insulating layer may be different from the thickness of the upper electrode portions that transmit electrons

above the pores and they are properly determined from the needs in the production process and the like.

The other structural examples of the electron-emitting device of the present invention will be described using the schematic sectional views of Figs. 22A and 22B. As the structure of the electron-emitting bodies 6, the example of Fig. 21A will be used, but, without having to be limited to this structure, either one of the structures of the electron-emitting bodies of Figs. 21B, 21C, 21D, etc. can also be employed.

Fig. 22A is an example in which the conductive bodies 8 of the columnar shape and the electron-emitting bodies 6 are provided in the pores. In this case, existence of the conductive bodies 8 decreases the resistance of the region from the lower electrode to the electron-emitting bodies, so that the insulating layer can be formed in a sufficiently large thickness. This can decrease the capacitance between the lower electrode and the upper electrode, which is advantageous in driving.

Fig. 22B is an example in which an insulating layer of a thickness permitting tunneling is provided between the lower electrode 2 and the electron-emitting bodies 6 in the pores, thereby forming a nonlinear device of metal/insulating layer/ carbon. This structure imparts the function of current limitation. This structure can prevent current fluctuation due to

discharge or the like and in turn prevent damage to the electron-emitting device during driving of the electron-emitting device of the present invention. A specific production method for producing the insulating metal oxide layer in the thickness permitting tunneling will be described hereinafter.

There are a variety of methods for producing the above electron-emitting device, among which an example is schematically illustrated in the production step diagram of Fig. 23. An example of the production method of the electron-emitting device of Fig. 21D will be described referring to Fig. 23.

(Step 1) Step of forming the lower electrode of the metal or the semiconductor on the substrate

The substrate 1 is cleaned well with detergent, pure water, and organic solvent or the like, the material for the lower electrode is deposited by vacuum evaporation, sputtering, or the like, and thereafter the lower electrode 2 is formed on the substrate, for example, by the photolithography technology. The lower electrode may also be formed by electrolytic crystallization.

(Step 2) Step of anodizing the lower electrode

The anodic oxidation system will be first described herein using the conceptual drawing thereof illustrated in Fig. 15. Numeral 51 denotes an anodic oxidation tank, 52 an anodic oxidation electrolyte

solution, 53 an electrode, 54 an anodic oxidation power supply, 55 a temperature controller for controlling the temperature of the anodic oxidation electrolyte solution 52, 56 a vessel for water circulating in the
5 temperature controller, and 57 the circulating water for control of temperature.

The anodic oxidation electrolyte solution 52 for the metal such as Al is an aqueous solution of one selected from inorganic acids such as sulfuric acid,
10 sulfamic acid, and phosphoric acid, and organic acids such as oxalic acid, malonic acid, and succinic acid, and the substance added thereto as solvent is polyhydric alcohol such as ethylene glycol, glycerin, or dextrin. On the other hand, the electrolyte
15 solution for Si is an aqueous solution of HF. Further, an oxidation process such as thermal oxidation may be further added.

The electrode 53 is the metal such as Pt. The anodic oxidation of the lower electrode is effected by
20 energization from the power supply 54 with the electrode 53 as a cathode and the substrate 1 as an anode. The geometrical structure of the anodic oxide layer can be controlled by production conditions. Specifically, the spacing between the pores can be
25 controlled by the anodic oxidation voltage, the depths of the pores by the anodic oxidation time, and the diameters of the pores by such conditions as the

composition of the electrolyte solution, the voltage, the current. Further, control of the regular pores or the irregular pores can also be made by control of these conditions.

5 Next, the substrate with the anodic oxide layer formed thereon is dipped in the anodic oxidation electrolyte solution or the like to adjust the diameter of the pores and the thickness of the dense oxide film. (This step will be called widening.) Then the
10 substrate is washed well with water and then dried in vacuum.

(Step 3) Step of forming the upper electrode on the metal or the semiconductor thus anodized

15 The upper electrode is formed in the thickness of several nm to several ten nm in the same manner as the lower electrode was.

(Step 4) Step of forming the electron-emitting bodies in the pores of the anodic oxide layer (under existence of organic material of gas state)

20 This step is a step of forming carbon in the pores of the aforementioned anodic oxide layer by applying the voltage to the upper electrode and lower electrode under existence of the organic material of a gas state. The carbon formed in this step is, for
25 example, graphite (including so-called HOPG, PG, and GC). HOPG indicates the almost perfect graphite crystal structure, PG somewhat disordered crystal

structure having crystal grains of 20 nm or so, and GC more disordered crystal structure having the crystal grains of 2 nm or so. In addition, the carbon may also be non-crystalline carbon (which means amorphous carbon and, a mixture of amorphous carbon with fine crystals of the aforementioned graphite). Accordingly, the carbon is one similar to the upper electrode as described above.

The preferred gas pressure of the organic substance for formation of the carbon differs depending upon the aforementioned application form, the shape of the vacuum vessel, the type of the organic substance, and so on and is thus properly determined according to the circumstances. An appropriate organic substance can be selected from aliphatic hydrocarbons of alkane, alkene, and alkyne, aromatic hydrocarbons, alcohols, aldehydes, ketones, amines, organic acids such as phenol, carboxylic acid, and sulfonic acid, and so on. Specific examples of such substances include saturated hydrocarbons represented by C_nH_{2n+2} such as methane, ethane, and propane, unsaturated hydrocarbons represented by the composition formula of C_nH_{2n} or the like such as ethylene and propylene, benzene, toluene, methanol, ethanol, formaldehyde, acetaldehyde, acetone, methyl ethyl ketone, methylamine, ethylamine, phenol, formic acid, acetic acid, propionic acid, and so on.

The organic gas is also selected according to

the diameter of the pores formed in the anodic oxide layer. This is because adsorption of the organic gas is also dependent on the diameter of the pores.

During this process carbon is deposited from
5 the organic substance present in the ambience into the pores in the anodic oxide layer, whereby the device current I_f and emission current I_e change remarkably.

Completion of this step is determined while
measuring either one of the device current I_f and the
10 emission current I_e or the both.

The apertures of the upper electrode 4 above the pores can also be formed in the initial stage of application of the above voltage pulses in this step.

(Step 5) Stabilization step

15 This step is a step for stabilizing the characteristics of the electron-emitting device thus produced. This step is necessary, particularly, where the formation of the electron-emitting bodies is carried out according to step 4) described above. This
20 step is a step of removing intermediate products of the organic material and also removing the organic gas, water, oxygen, etc. adsorbing to the substrate etc. from the carbon in the pores of the anodic oxide layer in the above step, whereby the step can impart to the
25 device such a property that the device current and the emission current monotonically increase above a certain threshold against the voltage applied to the device.

This step is a step of exhausting the organic substance in the vacuum vessel and the evacuation apparatus for evacuating the vacuum vessel is preferably one not using oil in order to avoid influence of the oil from the apparatus on the characteristics of the device. Specifically, the evacuation apparatus can be selected from a sorption pump, an ion pump, and so on.

The partial pressure of the organic component in the evacuation apparatus is set to a partial pressure under which there is little carbon or carbon compound newly deposited, and is preferably not more than 1×10^{-8} Torr and particularly preferably not more than 1×10^{-10} Torr. It is further preferred that the whole of the vacuum apparatus be heated during evacuation of the inside of the vacuum apparatus so as to facilitate removal of molecules of the organic substance adsorbing to the inner wall of the vacuum apparatus and to the electron-emitting device. The heating condition at this time is desirably the temperature of 150 to 300 °C and the heating time of not less than several hours, but the heating condition is not limited particularly to this condition.

The ambience during driving after completion of the stabilization step is preferably maintained in the ambience at the end of the above stabilization operation, but it is not limited to this. Sufficient characteristics can be maintained by an ambience from

which the organic substance is removed adequately but the vacuum degree of which is a little degraded.

By employing such a vacuum ambience, deposition of new carbon substance can be suppressed, whereby the
5 device current I_f and emission current I_e are stabilized as a result.

(Step 6) Step of forming the upper electrode 4

Using a target of graphite, amorphous carbon, or the like, graphite, amorphous carbon, or the like is
10 deposited on the pores and on the upper electrode 4 by sputtering or the like.

Further, the stabilization step of step 5 is carried out, whereby the purpose of the above step 5 is further accomplished.

15 [Example 1 of the third embodiment]

The electron-emitting devices were produced in the same structure as in Figs. 7A and 7B. Production steps of the present example will be described specifically.

20 (Step 1: step of forming the lower electrodes of metal on substrate)

The substrate 1 was prepared by depositing SiO_2 in the thickness of 1 μm on soda lime glass and the substrate 1 was washed well with detergent, pure water,
25 and organic solvent or the like. Then the material of Al for the lower electrodes was deposited in the thickness of 500 nm on the substrate by sputtering and

thereafter the lower electrode wires 81 were formed in stripes on the substrate 1 by the photolithography technology. For using parts of the lower electrode wires 81 as terminals, they were covered with a known mask resin for plating.

(Step 2: step of anodizing the lower electrodes)

Using the apparatus of Fig. 15, the anodic oxidation was carried out to anodize parts of the Al lower electrodes prepared in (step 1).

The anodic oxidation electrolyte solution 52 was an aqueous solution of oxalic acid 30 g/l. The electrode 53 was a Pt electrode. The anodic oxidation was carried on at 5 °C for five minutes by the constant voltage of 40 V from the power supply 55 with the cathode of the electrode 53 and the anode of the lower wires 81 provided on the substrate 1. On this occasion, the initial current density was 300 mA/cm², but the current density decreased with progress of the anodic oxidation and thereafter increased once to be saturated. Then the substrate with the anodic oxide layers was immersed in an aqueous solution of phosphoric acid for thirty minutes to remove the dense anodic oxide layer and thereafter washed well with water.

(Step 3: step of forming columnar metal in the pores of the anodic oxide layers)

Formation of the columnar metal in the pores

was carried out using the apparatus of Fig. 16. In Fig. 16, portions with the same reference numerals as those in Fig. 15 indicate like portions. Numeral 91 represents a counter electrode for electrolytic
5 deposition of metal, which is a counter electrode made of an inactive electrode such as carbon or Pt, or the same material as the electrodeposited metal. Numeral 92 indicates a container for a metal electrodeposition liquid, 93 a power supply for electrodeposition, and 94
10 an electrodeposition solution containing the metal.

In this step Ni was electrodeposited by the constant current at the current density of 1 mA/cm^2 , using the Pt electrode as the counter electrode 91 and 5 % NiSO_4 and 4 % H_3BO_3 as the electrodeposition
15 solution 94 containing the metal. An electrodeposition amount of columnar Ni was controlled by time and the columnar Ni was formed in each pore. The electrodeposition time was 100 seconds.
(Step 4: step of forming the upper electrode on the
20 metal or the semiconductor thus anodized)

The upper electrode 82 was made of Pt in the thickness of 10 nm in the same manner as the lower electrodes were.
(Step 5: step of forming carbon in the pores of the
25 anodic oxide layers (under existence of organic material of gas state))

The substrate 1 was set in the vacuum chamber

also serving as a measuring device and the voltage was applied to the upper electrode and lower electrodes under an ambience containing gas of acetone at 10^{-1} Pa. In step 5, the rectangular waves of the voltage waveform having the pulse width T_1 of 1 ms and the pulse spacing T_2 of 10 ms in the pulse waveform of Fig. 6A were applied for twenty minutes with the lower electrode side at the higher potential. After that, the upper electrode side was kept at the higher potential and the voltage was applied for 20 minutes. Thereafter, the system was evacuated and the substrate was taken out.

(Step 6: stabilization step)

Then the substrate was set in the vacuum chamber of the sputtering apparatus and the chamber was evacuated well. Thereafter, the chamber was evacuated for two hours while being heated at 300 °C.

(Step 7: step of forming the upper electrode)

Next, with a target of graphite, carbon was deposited in the thickness of 45 nm by sputtering, thereby forming the upper electrode.

Then the substrate was set in the vacuum process system of Fig. 5 and the voltage was applied to the lower electrode and upper electrode of each device, and to the anode electrode to measure the currents (the device current and emission current), and the device voltage characteristics. The electron beam was

observed by luminescence of the fluorescent member set at the anode. After the measurements, the sample thus formed was then observed with the electron microscope, TEM, and so on.

5 [Comparative Example]

An MIM type electron-emitting device was produced as a comparative example.

10 The following steps were carried out; (step 1: step of forming the lower electrode of metal on the substrate), (step 2: step of anodizing the lower electrode), and (step 4: step of forming the upper electrode on the metal or the semiconductor thus anodized). Steps 1 and 4 are the same as in the example, but the anodic oxidation conditions of step 2
15 were changed. The anodic oxidation conditions were as follows; the anodic oxidation solution was an ammonium tartrate solution, constant current anodic oxidation was carried out at $500 \mu\text{A}/\text{cm}^2$, and the thickness of the insulating layer was 6 nm.

20 Each device demonstrated the monotonically increasing characteristics for both the device current and the emission current over their threshold. The current was negligible below the threshold (V_{th}). When the electron beam was observed by luminescence of the
25 fluorescent member, it was equivalent to that of the MIM electron-emitting device of the comparative example. The electron emission efficiency of the

comparative example was 0.1 %, whereas that of the example was 5 % on average. At the same time, the electron emission current increased corresponding to the efficiency.

5 In observation of cross section with the electron microscope, the regular pores were observed in the anodic oxide layers. The diameter of the pores was 80 nm. The polelike Ni metal and carbon were stacked in the pores and there was the small gap of 5 to 10 nm
10 with respect to the upper electrode.

 The above verified that the spread of electron beam was equivalent to that of the MIM electron-emitting device and that the electron-emitting devices demonstrated high electron emission efficiency and
15 emission current. Thanks to the stabilization step, both the device current and emission current showed the monotonically increasing characteristics having the threshold V_{th} without occurrence of the voltage-controlled negative resistance characteristics, or the
20 VCNR characteristics.

[Example 2 of the third embodiment]

 In the present example the substrate was constructed in the device layout similar to Example 1 of the third embodiment. In the present example, the
25 anodic oxidation conditions of aluminum and the diameter of the pores in Example 1 were changed and influence thereof was investigated.

(Step 1: step of forming the lower electrodes of metal on the substrate)

This step was carried out in the same manner as step 1 of Example 1.

5 (Step 2: step of anodizing the lower electrodes)

This step was carried out in the same manner as step 2 of Example 1.

Next, the diameters of the pores were changed by changing the time for which the substrate with the anodic oxide layers formed therein was immersed in the aqueous solution of phosphoric acid. The diameters of the pores were 20, 30, 40, 50, and 80 nm.

(Step 3: step of forming columnar metal in the pores of the anodic oxide layers)

15 The formation of columnar metal in the pores was carried out using the apparatus of Fig. 16. In this step, Ni was electrodeposited using the Pt electrode as the counter electrode 91, 5 % NiSO₄ and 4 % H₃BO₃ as the electrodeposition solution 94 containing the metal, and the alternating current of 60 Hz at the current density of 1 mA/cm². An electrodeposition amount of columnar Ni was controlled by time and columnar Ni was formed in each pore. Ni also migrated into the dense oxide layer at the bottom of the pores of the anodic oxide layers, so that the columnar Ni was electrically connected to the lower electrode.

(Step 4: step of forming the upper electrode on the

metal or the semiconductor thus anodized)

This step was not carried out.

(Step 5: step of forming the electron-emitting bodies
in the pores of the anodic oxide layers)

5 A layer of W was deposited in the thickness of
7 nm by sputtering and thereafter reduced and
aggregated in hydrogen gas, thereby forming small
particles thereof. The grain size of the small
particles was 10 nm.

10 (Step 6: stabilization step)

Next, the substrate was set in the vacuum
chamber of the sputtering apparatus and the chamber was
evacuated well.

(Step 7: step of forming the upper electrode)

15 Next, with a target of graphite, carbon was
deposited in the thickness of 20 nm by sputtering,
thereby forming the upper electrode.

According to observation with the electron
microscope, the carbon was also able to cover the
20 regions above the pores as long as the diameter of the
pores was below 40 nm; the carbon above the pores
failed to cover parts or the whole of the regions above
the pores if the diameter of the pores was not less
than 50 nm. This proved that the thickness t of the
25 upper electrode needs to satisfy the following
condition against the length L of the pores:

$$0.5 \times L \leq t.$$

In the same manner as the example, it was verified that the devices having the pore diameters not more than 40 nm were able to emit electrons in the beam spread equivalent to that of the comparative example.

5 [Example 3 of the third embodiment]

In the present example the substrate was constructed in the device layout similar to Example 1 of the third embodiment. In the device structure of Fig. 21B, samples were formed with a variety of
10 thicknesses of the upper electrode and influence thereof was investigated. The same steps as in Example 1 were carried out except for steps 5 and 7.

(Step 1: step of forming the lower electrodes of metal on the substrate)

15 This step was carried out in the same manner as step 1 of Example 1.

(Step 2: step of anodizing the lower electrodes)

This step was carried out in the same manner as step 2 of Example 1.

20 (Step 3: step of forming columnar metal in the pores of the anodic oxide layers)

This step was carried out in the same manner as step 3 of Example 1.

(Step 4: step of forming the upper electrode on the
25 metal or the semiconductor thus anodized)

This step was carried out in the same manner as step 4 of Example 1.

(Step 5: step of forming the electron-emitting bodies in the pores of the anodic oxide layers)

W was deposited in the thickness of 7 nm by sputtering and thereafter reduced and aggregated in hydrogen gas, thereby forming small particles thereof.
(Step 6: stabilization step)

Then the substrate was set in the vacuum chamber of the sputtering apparatus and the chamber was evacuated well. After that, the chamber was evacuated for two hours while being heated at 300 °C.
(Step 7: step of forming the upper electrode)

Next, with a target of graphite, the carbon was deposited in either thickness of 10, 35, 50, 65, 80, and 200 nm by sputtering, thereby forming the upper electrode.

Then the substrate was set in the vacuum process system of Fig. 5 and the voltage was applied to the lower electrode and upper electrode of each device, and to the anode electrode to measure the currents (the device current and emission current), and the device voltage characteristics. Further, the electron beam was observed by luminescence of the fluorescent member placed at the anode.

The electron beam was more spread in the device of the thickness of 10 nm than in the comparative example. The devices having the thicknesses of 35, 50, 65, and 80 nm were equivalent to the comparative

example. With the device having the thickness of 200 nm, the emission current was too small to measure.

As illustrated in Fig. 24, the electron emission current was very high at the upper electrode thickness of 10 nm and showed exponential dependence in the range of 35, 50, 65, and 80 nm. The current at the thickness of 200 nm was of the noise level. The mean free path of carbon was calculated based on this result.

According to observation of the forms of the upper electrodes, the upper electrode failed to cover the regions above the pores in the samples of the thicknesses of 10 and 35 nm and holes were observed in the upper electrode. There were no holes observed in the regions above the pores in the samples having the thicknesses of 50, 65, and 80 nm.

The above results verified the following. There is an optimum value of the thickness of the upper electrode against the diameter of the pores. If the upper electrode is too thin, the upper electrode will fail to cover the pores and the electron beam will spread. Within the optimum range, the spread of beam is decreased and the emission current decreases depending upon the thickness. Further, sufficient emission current can be obtained if the upper electrode has the thickness not more than 2λ as described previously.

[Example 4 of the third embodiment]

The present example is an example of application to the image pickup device of Figs. 9A and 9B described previously, in which a plurality of
5 electron-emitting devices prepared by the same method as in Example 1 of the third embodiment are placed in a two-dimensional array on the substrate.

The production method of the image pickup device of the present example is the same as in the
10 first embodiment. The image pickup device produced in this way was operated based on the principle of operation stated previously, whereupon the signal current was obtained in 1:1 correspondence to the size of the electron-emitting device, thereby verifying the
15 operation.

[Example 5 of the third embodiment]

The present example is an example of construction of the display device of Figs. 10A and 10B described previously, in which a plurality of electron-
20 emitting devices produced by the same method as in Example 1 of the third embodiment are arrayed in a two-dimensional pattern on the substrate. The production method of the display device of the present example is the same as in the first embodiment. The display
25 device produced in this way was operated based on the principle of operation discussed previously, and a bright image was displayed in high definition.

[Fourth Embodiment]

Fig. 25A is a sectional view of the electron-emitting device of the fourth embodiment. Fig. 25B is a partly enlarged schematic view of part A in the sectional view of Fig. 25A.

The substrate 1 to be employed herein can be selected from quartz glass, glass with a decreased content of impurity such as Na, soda lime glass, a glass substrate obtained by depositing SiO_2 on soda lime glass by sputtering or the like, ceramics such as alumina, an Si substrate, an Si substrate with a deposited layer of SiO_2 , and so on. Particularly, when the substrate 1 is a semiconductor substrate, a driver or the like for driving the electron-emitting device can also be mounted simultaneously.

The lower electrode 2 is selected from metals, such as Al, Ta, Nb, Ti, Zr, Hf, or Si, and semiconductors that can undergo anodic oxidation. The thickness of the lower electrode 2 is properly determined according to the thickness of the anodic oxide layer, the electrical resistance of the lower electrode, and so on. The materials for the lower electrode are not limited to only the metals that can be anodized, but they may also be of a stack form of a metal that cannot be anodized and a metal that can be anodized.

The anodic oxide layer 3 is formed by anodic

oxidation of the lower electrode in part. In the anodic oxide layer 3 there exist regular or irregular pores 5. This will also be called porous structure in the present specification. The regular or irregular pores 5 can be formed by selecting anodic oxidation conditions including a composition of an anodic oxidation bath, the temperature of the bath, the voltage, the time, etc., according to the material for the lower electrode 2. Preferably, the regular pores are selected. Diameters of the pores range from several ten nm to several hundred nm and depths thereof from several ten nm to several thousand nm. The density of the pores is 10^8 to 10^{12} pores/cm². The shape of the pores is not limited only to the circle, but the ellipse, square, etc. can also be applied to the electron-emitting devices of the present invention. The variety of shapes can also be formed using the focused ion beam or the like. Therefore, the expression "length of pore" will also be used in place of the diameter of pore in the present invention. In each pore 5 the carbon 6 electrically connected to the lower electrode 2 is formed in the polelike shape filling a part of the pore. Electrons are emitted from the peripheral part of the pole in each pore or from the region of the top surface of the pole and the emission of electrons is determined by the shape of the pole and the shape of the upper electrode on the anodic

oxide layer. Accordingly, electrons are emitted in a linear shape or in a linear and surface shape from each pore, according to the pore.

5 The carbon may also be formed in the similar fashion from the side of the upper electrode 4.

There is a gap created between the carbon formed on the lower electrode 2, and the upper electrode or, in the case where the carbon is also formed from the side of the upper electrode 4, between
10 the carbon from the upper electrode 4 side and the carbon formed on the lower electrode 2. This gap is preferably several nm to several ten nm, and is properly determined according to the time of the step of applying the voltage to the upper electrode and
15 lower electrode under existence of the organic material described hereinafter, the voltage applied, and so on.

The upper electrode is formed above the anodic oxide layer and is made preferably of a material having a high melting point, such as Pt, W, Mo, or Hf.

20 Structural examples of the above electron-emitting device of the present invention will be explained using the schematic sectional views of Figs. 26A and 26B. In Figs. 26A and 26B, numeral 207 designates a small gap and the same portions as in
25 Figs. 25A and 25B are denoted by the same reference numerals. There are two kinds of structures illustrated in Figs. 26A and 26B, but other structures

may also be employed, without having to be limited to these illustrated structures. The following describes examples using the metal for the upper electrode and the lower electrode, but they may also be made of the semiconductor.

The structure of Fig. 26A is metal (lower electrode) / metal oxide layer / pores, each having a carbon electron-emitting body 6 / vacuum / metal (upper electrode) 4 formed in the regions except for the regions above the pores. The structure of Fig. 26B is metal (lower electrode) / pores, each having an electron-emitting body 6 / vacuum / metal (upper electrode) 4 formed in the regions except for the regions above the pores.

In the structure of Fig. 26A, the metal oxide layer 3 is obtained on the occasion of anodic oxidation of the lower electrode, and two structural regions, a dense film structural region without pores and a film structural region with pores, can be obtained in this metal oxide layer 3, depending upon the anodic oxidation conditions. As illustrated in Fig. 26A, the formation of the dense film structural region of the above metal oxide layer between the lower electrode 2 and the electron-emitting bodies 6 in the pores results in forming a nonlinear device in the structure of metal / insulator / carbon, so as to impart the function of current limitation, which can prevent the current

fluctuation in discharge or the like on the occasion of driving the electron-emitting device of the present invention and which can in turn prevent damage to the electron-emitting device. A specific production method
5 of the above metal oxide layer will be described hereinafter, but it is first formed, for example, under conditions for forming the porous metal oxide and thereafter the thickness of the dense film structural region is adjusted in the widening step of pores
10 described hereinafter.

The structure of Fig. 26B does not have the metal oxide layer without the pores and the electron-emitting bodies (carbon) in the pores are electrically connected directly to the lower electrode. This
15 structure is constructed by anodizing the lower electrode, thereafter sufficiently widening the pores by the widening step of pores described hereinafter, and further forming the electron-emitting bodies (carbon) in the pores, whereby the lower electrode
20 becomes electrically connected to the electron-emitting bodies in some cases. On this occasion, the metal oxide layer without the pores between the lower electrode and the metal oxide layer with the pores may be electrically broken by the pulse voltage applied in
25 the step of forming the carbon in the pores of the anodic oxide layer described hereinafter, so that the electron-emitting bodies are electrically connected to

the lower electrode. In the structure of Fig. 26B, the electron-emitting device is also provided with the nonlinear characteristics by tunneling between the electron-emitting bodies and the vacuum. The
5 electrical connection with the lower electrode can also be achieved in such a way that the metal is precipitated by alternating current into the pores of the anodic oxide film by the coloring method of the anodic oxide film conventionally well known whereupon
10 the precipitating metal into the pores migrates into the dense anodic oxide film to implement the electrical connection. The above "vacuum" is one equivalent to the vacuum ambience in which the substrate with the electron-emitting device formed thereon is set.

15 In the electron-emitting device of the present invention described above, the carbon making the electron-emitting bodies is preferably at least one of graphite, amorphous carbon, and diamondlike carbon, particularly, in terms of heat resistance, stability of
20 electron emission characteristics, and improvement in repeatability, as stated previously.

Next described is an electron-emitting mechanism of the electron-emitting device of the present invention in the structural examples of Fig.
25 26A and Fig. 26B.

In the surface conduction electron-emitting device stated previously in the related background art,

according to Japanese Laid-open Patent Application No.
9-082214, electrons are once emitted into the vacuum
outside the anode from a certain position on the anode
side (which is also called the higher potential side)
5 of the fissure region, in the fissure region of the
surface conduction electron-emitting device. The
electrons once emitted move in the electric field
created by the cathode (which is also called the lower
potential side) and the anode, and electrons flying
10 over the singular point (hereinafter referred to as a
stagnation point) of the electric field are attracted
to the anode plate by the electric field created by the
voltage applied to the anode plate set opposite to the
electron-emitting device with intervention of vacuum.
15 The electrons that do not reach the singular point of
the electric field drop onto the anode, and some of
electrons are scattered here to be deflected and again
emitted into the vacuum. Electrons moving over the
singular point of the electric field as a result of
20 repetition of this scattering also reach the anode
plate.

It is described in the prior art application
that, in order to largely increase the electron
emission efficiency, the electric field needs to be set
25 in such conditions that most of the electrons once
emitted are attracted to the anode plate without
dropping onto the anode in the above mechanism of

electron emission and that the electron emission efficiency can be increased by providing the field correcting electrode outside the device electrode and applying a sufficiently higher voltage thereto than the voltage applied to the device for emission of electron.

5 In contrast with it, in the case of the electron-emitting device of the present invention, when the higher potential is applied to the upper electrode and the lower potential than that to the upper electrode is applied to the lower electrode, a potential difference between them is placed in the small gap between the upper electrode 4 and the electron-emitting body 6, whereupon electrons are emitted from the electron-emitting bodies into the vacuum. Since a strong electric field is placed in the small gap corresponding to the fissure of the

10 aforementioned prior art, the electrons emitted from the electron-emitting bodies 6 into the vacuum collide with the upper electrode 4 to be scattered, just as in the case of the surface conduction electron-emitting device described previously in the related background art. It is, however, assumed that, in the case of the electron-emitting device of the present invention, the electrons reach the anode plate over the singular point

15 of the electric field without repetition of scattering.

20 Now, the principle of the electron-emitting device of the present invention will be described using

Fig. 27. Fig. 27 is a diagram to explain the principle of the electron-emitting device of the present invention. In the figure, h indicates the distance between the electron-emitting device and the anode electrode, d the length of pore, and V_a the potential of the anode electrode.

Here, the following discussion is made with focusing attention on electrons emitted from the side of the upper electrode 4 of the electron-emitting body 6 on one side. Since the electrons are emitted along the periphery of the pore from the electron-emitting body 6, the electrons are also emitted from the upper electrode opposed to the upper electrode 4. The electrons emitted from the electron-emitting body 6 into the vacuum collide with the upper electrode 4 because of the electric field placed in the small gap 207 to be first scattered isotropically. Since the strong electric field from the opposite upper electrode present at the very close distance considerably constricts the stagnation point described above, as compared with that in the conventional surface conduction electron-emitting device, the electrons scattered isotropically reach the anode plate without repetitive scattering, mostly after scattered only once. On the other hand, where the thickness of the upper electrode 4 is small, the electrons also reach the anode plate, mostly after scattered only once,

without repetitive scattering. It is considered that the above accounts for the increase of the electron emission efficiency. On the other hand, the same can also be applied to the electron-emitting bodies 6
5 having the electron-emitting regions formed in the rim shape of the pores, and this is conceivably the cause of increase of the electron emission efficiency.

An important factor for the effect of the electric field of the opposite upper electrode is the
10 diameter of the aperture. Supposing the work function of the electron-emitting body is 4 to 5.5 eV, the electric field for emission of electrons into the small gap is not less than 10^7 V/cm. When the stagnation point being the singular point of the electric field as
15 defined in the aforementioned prior art is applied to the prior art electron-emitting device and the present invention, the distance X_s of the stagnation point without 34 is represented by the following equation.

$$X_s = h \cdot V_f / (\pi \cdot V_a)$$

20 On the other hand, the stagnation point X_s' with 34 is indicated by the following equation.

$$X_s' = h \cdot V_f / \{ \pi \cdot V_a + h \cdot V_f / (\pi \cdot d) \}$$

Therefore, the smaller the diameter of the aperture, the more the stagnation point is constricted.

25 Particularly, from the reason that the constriction effect of the stagnation point can be expected even at the upper electrode voltage of several ten V, the

diameter of the aperture is preferably not more than 0.5 μm and more preferably not more than 0.2 μm . Further, the thickness of the upper electrode is preferably as thin as possible in order to suppress the repetitive scattering and, from examples, the thickness is preferably not more than 0.2 μm in terms of the efficiency. For specifying the condition by the thickness of the upper electrode, the small gap contributing to the emission of electrons has to be present at the edge of the upper electrode. From the viewpoint of suppressing the repetitive scattering, it corresponds to the distance from the small gap to the upper surface of the upper electrode.

The driving voltage is a low driving voltage, because the gap is small. Since the direction of the voltage to draw the electrons is coincident with the direction toward the anode plate, a spread of the electron beam, though scattered isotropically, is suppressed relatively.

There are a variety of methods for producing the electron-emitting device described above, among which a first production method will be described referring to the production step diagram of Fig. 28.

(Step 1) Step of forming the lower electrode of the metal or the semiconductor on the substrate

The substrate 1 is cleaned well with detergent, pure water, and organic solvent or the like, the

material for the lower electrode is deposited by vacuum evaporation, sputtering, or the like, and thereafter the lower electrode 2 is formed on the substrate, for example, by the photolithography technology. The lower
5 electrode may also be formed by electrolytic crystallization.

(Step 2) Step of anodizing the lower electrode

The conceptual drawing of the anodic oxidation system was already described referring to Fig. 15. The
10 electrode 53 is the metal such as Pt. The anodic oxidation of the lower electrode is effected by energization from the power supply 54 with the electrode 53 as a cathode and the substrate 1 with the lower electrode formed thereon, as an anode. The
15 geometrical structure of the anodic oxide layer can be controlled by production conditions. Specifically, the spacing between the pores can be controlled by the anodic oxidation voltage, the depths of the pores by the anodic oxidation time, and the diameters of the
20 pores by such conditions as the composition of the electrolyte solution, the voltage, the current. Further, control of the regular pores or the irregular pores can also be made by control of these conditions.

Next, the substrate with the anodic oxide layer
25 formed thereon is dipped in the anodic oxidation electrolyte solution or the like to adjust the diameter of the pores and the thickness of the dense oxide film.

(This step will be called widening.) Then the substrate is washed well with water and then dried in vacuum.

(Step 3) Step of forming the upper electrode on
5 the metal or the semiconductor thus anodized

The upper electrode is formed in the thickness of not more than 200 nm in the same manner as the lower electrode was.

(Step 4) Step of forming the electron-emitting
10 bodies in the pores of the anodic oxide layer (under existence of organic material of gas state)

This step is a step of forming carbon in the pores of the aforementioned anodic oxide layer by applying the voltage to the upper electrode and lower
15 electrode under existence of the organic material of a gas state. The carbon formed in this step includes, for example, graphite (including so-called HOPG, PG, and GC). HOPG indicates the almost perfect graphite crystal structure, PG somewhat disordered crystal
20 structure having crystal grains of 20 nm or so, and GC more disordered crystal structure having the crystal grains of 2 nm or so. In addition, the carbon may also be non-crystalline carbon (which means amorphous carbon and, a mixture of amorphous carbon with fine crystals
25 of the aforementioned graphite). The vacuum process system used in this step was already described referring to Fig. 5.

Particularly, where the carbon of the electron-emitting bodies is deposited from the lower electrode so as to form a constant gap with respect to the upper electrode, the carbon can be formed by applying the
5 voltage with the upper electrode at the lower potential and the lower electrode at the higher potential. After the voltage is applied with the upper electrode at the lower potential and the lower electrode at the higher potential, the voltage is further applied with the
10 upper electrode at the higher potential and the lower electrode at the lower potential, whereby the carbon is also deposited on the upper electrode after formation of a constant gap above the deposition of carbon of the electron-emitting bodies from the lower electrode,
15 thereby forming a constant separation from the upper electrode. Since the position of the gap affects the electron emission characteristics as described previously, it is preferable to deposit the carbon from the lower electrode and then form the constant gap from
20 the upper electrode.

The preferred gas pressure of the organic substance for formation of the carbon differs depending upon the aforementioned application form, the shape of the vacuum vessel, the type of the organic substance,
25 and so on and is thus properly determined according to the circumstances. An appropriate organic substance can be selected from aliphatic hydrocarbons of alkane,

alkene, and alkyne, aromatic hydrocarbons, alcohols, aldehydes, ketones, amines, organic acids such as phenol, carboxylic acid, and sulfonic acid, and so on. Specific examples of such substances include saturated
5 hydrocarbons represented by C_nH_{2n+2} such as methane, ethane, and propane, unsaturated hydrocarbons represented by the composition formula of C_nH_{2n} or the like such as ethylene and propylene, benzene, toluene, methanol, ethanol, formaldehyde, acetone, methyl ethyl
10 ketone, methylamine, ethylamine, phenol, formic acid, acetic acid, propionic acid, and so on. The organic gas is also selected according to the diameter of the pores formed in the anodic oxide layer. This is because adsorption of the organic gas is also dependent
15 on the diameter of the pores.

During this process carbon is deposited from the organic substance present in the ambience into the pores in the anodic oxide layer, whereby the device current I_f and emission current I_e change remarkably.

20 Completion of this step is determined while measuring either one of the device current I_f and the emission current I_e or the both.

The apertures of the upper electrode 4 above the pores, as illustrated in Figs. 26A and 26B, can
25 also be formed in the initial stage of application of the above voltage pulses in this step.

(Step 5) Stabilization step

This step is a step for stabilizing the characteristics of the electron-emitting device thus produced. This step is a step of removing intermediate products of the organic material and also removing the organic gas, water, oxygen, etc. adsorbing to the substrate etc. from the carbon in the pores of the anodic oxide layer in the above step, whereby the step can impart to the device such a property that the device current and the emission current monotonically increase above a certain threshold against the voltage applied to the device. This step is a step of exhausting the organic substance in the vacuum vessel and the evacuation apparatus for evacuating the vacuum vessel is preferably one not using oil in order to avoid influence of the oil from the apparatus on the characteristics of the device. Specifically, the evacuation apparatus can be selected from a sorption pump, an ion pump, and so on.

The partial pressure of the organic component in the evacuation apparatus is set to a partial pressure under which there is little carbon or carbon compound newly deposited, and is preferably not more than 1×10^{-8} Torr and particularly preferably not more than 1×10^{-10} Torr. It is further preferred that the whole of the vacuum apparatus be heated during evacuation of the inside of the vacuum apparatus so as to facilitate removal of molecules of the organic

substance adsorbing to the inner wall of the vacuum apparatus and to the electron-emitting device. The heating condition at this time is desirably the temperature of 150 to 300 °C and the heating time of
5 not less than several hours, but the heating condition is not limited particularly to this condition.

The ambience during driving after completion of the stabilization step is preferably maintained in the ambience at the end of the above stabilization
10 operation, but it is not limited to this. Sufficient characteristics can be maintained by an ambience from which the organic substance is removed adequately but the vacuum degree of which is a little degraded.

By employing such a vacuum ambience, deposition
15 of new carbon substance can be suppressed, whereby the device current I_f and emission current I_e are stabilized as a result.

Next described is a second production method where the carbon or diamondlike carbon is formed in
20 liquid. The method will be described as to the case where the device is constructed in the structure of either Fig. 26A or Fig. 26B.

(Step 1) Step of forming the lower electrode of the metal or the semiconductor on the substrate

25 This step is carried out in the same manner as the method described in step 1 of the first production method.

(Step 2) Step of anodizing the lower electrode

This step is also carried out in the same manner as the method described in step 2 of the first production method and, after the anodic oxidation and widening step, the anodized substrate is washed with water and is taken into the electrolytic tank of (step 3).

(Step 3) Step of forming the electron-emitting bodies in the pores of the anodic oxidation layer (under existence of organic material of liquid state)

This step is a step of forming the electron-emitting bodies in the pores of the aforementioned anodic oxide layer by applying the voltage to the electrode 53 of Fig. 15 and the lower electrode under existence of an organic material of a liquid state.

Using the apparatus similar to Fig. 15, electrolysis is conducted in the electrolyte solution of alcohol between the cathode of the lower electrode side and the anode, whereby diamondlike carbon can be deposited from the lower electrode side in the pores formed by the anodic oxidation.

The diamondlike carbon grows in the columnar shape in the pores with a lapse of the electrolytic time.

(Step 4) Step of forming the upper electrode on the metal or the semiconductor thus anodized

The upper electrode is formed in the thickness

of not more than 20 nm in the same manner as the lower electrode was.

(Step 5) Stabilization step

5 This step is carried out in the same manner as the stabilization step described in step 5 of the first production method.

[Example 1 of the fourth embodiment]

10 The electron-emitting devices were produced in the same structure as in Figs. 7A and 7B. Production steps of the present example will be described specifically.

(Step 1: step of forming the lower electrodes of metal on substrate)

15 The substrate 1 was prepared by depositing SiO_2 in the thickness of 1 μm on soda lime glass and the substrate 1 was washed well with detergent, pure water, and organic solvent or the like. Then the material of Al for the lower electrodes was deposited in the thickness of 500 nm on the substrate by sputtering and
20 thereafter the lower electrode wires 71 were formed in stripes on the substrate 1 by the photolithography technology. For using parts of the lower electrode wires 71 as terminals, they were covered with a known mask resin for plating.

25 (Step 2: step of anodizing the lower electrodes)

Using the apparatus of Fig. 15, the anodic oxidation was carried out to anodize parts of the Al

lower electrodes prepared in (step 1).

The anodic oxidation electrolyte solution 52 was an aqueous solution of oxalic acid 30 g/l. The electrode 53 was a Pt electrode. The anodic oxidation was carried on at 5 °C for five minutes by the constant voltage of 40 V from the power supply 55 with the cathode of the electrode 53 and the anode of the lower wires 71 provided on the substrate 1. On this occasion, the initial current density was 300 mA/cm², but the current density decreased with progress of the anodic oxidation and thereafter increased once to be saturated. Then the substrate with the anodic oxide layers was immersed in an aqueous solution of phosphoric acid for thirty minutes to remove the dense anodic oxide layer and thereafter washed well with water.

(Step 3: step of forming columnar metal in the pores of the anodic oxide layers)

Formation of the columnar metal in the pores was carried out using the apparatus of Fig. 16. In this step Ni was electrodeposited by the constant current at the current density of 1 mA/cm², using the Pt electrode as the counter electrode 91 and 5 % NiSO₄ and 4 % H₃BO₃ as the electrodeposition solution 94 containing the metal. An electrodeposition amount of columnar Ni was controlled by time and the columnar Ni was formed in each pore. The electrodeposition time

was 100 seconds.

(Step 4: step of forming the upper electrode on the metal or the semiconductor thus anodized)

5 The upper electrode 72 was made in the thickness of 10 nm in the same manner as the lower electrodes were.

(Step 5: step of forming carbon in the pores of the anodic oxide layers (under existence of organic material of gas state))

10 The substrate 1 was set in the vacuum chamber also serving as a measuring device and the voltage was applied to the upper electrode and lower electrodes under an ambience containing gas of acetone at 10^{-1} Pa. In step 3, three devices out of the five devices were
15 processed by applying the rectangular waves of the voltage waveform having the pulse width T1 of 1 ms and the pulse spacing T2 of 10 ms in the pulse waveform of Fig. 6A with the lower electrode side at the higher potential for fifteen minutes. Thereafter, the upper
20 electrode was kept at the higher potential and the voltage was applied for five minutes. At the same time, the current of device was monitored. The voltage was 17 V. The two remaining devices out of the five
25 devices were processed by applying the voltage of 17 V similarly in the pulse waveform of Fig. 6B for twenty minutes.

(Step 6: stabilization step)

Then the acetone gas was exhausted sufficiently and thereafter the system was evacuated for two hours while being heated at 300 °C.

Then the substrate was set in the vacuum
5 process system of Fig. 5 and the voltage was applied to the lower electrode and upper electrode of each device, and to the anode electrode to measure the currents (the device current and emission current) and the device
10 voltage characteristics. Further, electron beams were observed by luminescence of the fluorescent member placed at the anode. After the measurements, the sample thus formed was then observed with the electron microscope, TEM, and so on.

The device current and emission current both of
15 each device demonstrated the monotonically increasing characteristics over their threshold. The current was negligible below the threshold (called V_{th}). Values of emission current of the devices obtained with application of the pulses of Fig. 6A were equivalent to
20 those of the devices obtained with application of the pulses of Fig. 6B and, therefore, their emission efficiencies were also equivalent.

In observation with the electron emission, the regular pores were observed in the anodic oxide layers.
25 The density of the pores was 1×10^9 pores/cm².

Further, cross-sectional samples were prepared and the inside of the pores was observed. The cross

sections of the devices were as illustrated in Fig. 29A and Fig. 29B. In Figs. 29A and 29B, the same reference symbols as those in Figs. 26A and 26B denote like portions. Fig. 29A is a cross section of the devices
5 in which carbon was formed by applying the pulses of Fig. 6A in step 5, while Fig. 29B is a cross section of the devices in which carbon was formed by applying the pulses of Fig. 6B in step 5. Numeral 111 represents columnar metal Ni, 112 carbon formed in the columnar
10 shape in the pores, 113 carbon formed on the upper electrode side, and 114 a small gap.

As illustrated in Fig. 29A, where the carbon was formed with application of the pulses of Fig. 6A, the Ni metal was deposited in the columnar shape 110 nm
15 high in the pores from the lower electrode 2 of Al and columnar amorphous carbon was further formed in the pores on the top surface of columnar Ni. Further, amorphous carbon was also formed similarly on the side of the upper electrode 4. A small gap was formed
20 between the carbon on the upper electrode 4 side and the carbon on the lower electrode 2 side and the gap was formed at the edge of the upper electrode. The gap was several nm. The thickness of the anodic oxide film was 150 nm.

25 On the other hand, where the carbon was formed with application of the pulses of Fig. 6B, as illustrated in Fig. 29B, the Ni metal was deposited in

the columnar shape in the pores on the lower electrode 2 of Al and columnar amorphous carbon was further formed in the pores on the top surface of columnar Ni. Further, amorphous carbon was also formed similarly on the side of the upper electrode 4. The carbon was formed to the position 20 nm apart from the bottom surface of the upper electrode and a small gap was formed between the two carbon layers. The gap was several nm.

The above proved the following. First, the metal is anodized, the columnar metal is formed in the pores, and the columnar carbon is formed in the pores on the top surface of the columnar metal. Second, the small gap of several nm is formed between the carbon films on the upper electrode side and on the lower electrode side. Third, the emission current and electron emission efficiency are equivalent as long as the small gap is located in the range of 20 nm from the bottom surface of the upper electrode. Since the distance from the gap to the top surface of the upper electrode is not more than 30 nm including the thickness of the upper electrode in the both examples, the probability is assumed to be low of loss of the electrons emitted from the lower electrode side, in the pores. Fourth, the stabilization step enables the device current and emission current to demonstrate the monotonically increasing characteristics without

occurrence of the voltage-controlled negative resistance characteristics, or the VCNR characteristics.

[Example 2 of the fourth embodiment]

5 In the present example the substrate was constructed in the device layout similar to Example 1 of the fourth embodiment. The upper electrode was formed in a variety of thicknesses and influence thereof was investigated. Step 1 to step 3, and step 6
10 were carried out in the same manner as in Example 1. The description of step 1 to step 3, and step 6 will be omitted herein and only steps 4 and 5 will be described in detail.

 (Step 1: step of forming the lower electrodes of metal
15 on the substrate)

 This step was carried out in the same manner as step 1 of Example 1.

 (Step 2: step of anodizing the lower electrodes)

 This step was carried out in the same manner as
20 step 2 of Example 1.

 (Step 3: step of forming columnar metal in the pores of the anodic oxide layers)

 This step was carried out in the same manner as step 3 of Example 1.

25 (Step 4: step of forming the upper electrode on the metal or the semiconductor thus anodized)

 The upper electrode 72 was formed in either of

four thicknesses of 5, 10, 100, and 500 nm on each substrate in the same manner as the lower electrodes, thus forming four substrates.

(Step 5: step of forming carbon in the pores of the
5 anodic oxide layers (under existence of organic material of gas shape))

Each substrate 1 was set in the vacuum chamber also serving as a measuring device and the voltage was applied to the upper electrode and lower electrode
10 under an ambience containing gas of acetone at 10^{-1} Pa. Three devices out of the five devices were processed by applying the rectangular waves of the voltage waveform having the pulse width T1 of 1 ms and the pulse spacing T2 of 10 ms in the pulse waveform of Fig. 6A for
15 fifteen minutes with the lower electrode side at the higher potential. After that, the upper electrode was kept at the higher potential and the voltage was applied for five minutes. At the same time, the current of device was monitored. The voltage was 17 V.
20 (Step 6: stabilization step)

This step was carried out in the same manner as step 2 of the Example 1.

Next, each substrate was set in the vacuum process system of Fig. 5 and the voltage was applied to
25 the lower electrode and upper electrode of each device, and to the anode electrode to measure the currents (the device current and emission current) and the device

voltage characteristics. Further, the electron beam was observed by luminescence of the fluorescent member placed at the anode.

Fig. 30 shows the relation between thickness of the upper electrode and electron emission efficiency. As shown in Fig. 30, the electron emission efficiency did not decrease below the thickness of about 200 nm and then decreased with increasing thickness of the upper electrode over 200 nm. The electron emission efficiency is defined as a ratio of emission current to device current. Further, the beam size also decreased.

In observation of the form of the upper electrode, particularly, in the case of the upper electrode having the large thickness, where the thickness was greater than the diameter of the pores, the inside of the pores was also covered in part. When the small gap was observed with section TEM, the small gap was formed at the edge of the bottom surface of the upper electrode in either sample, as in Example 1.

The above verified the following. First, the small gap is formed at the edge of the upper electrode, irrespective of the thickness of the upper electrode. Second, the emission current and electron emission efficiency decrease, depending upon the thickness of the upper electrode. This is assumed to be due to the high probability of loss at the upper electrode of the porous shape, of the electrons emitted from the lower

electrode side.

[Example 3 of the fourth embodiment]

In the present example the substrate was constructed in the device layout similar to Example 1 of the fourth embodiment. In the present example, SiO_2 was used as the insulating layer instead of the anodic oxide layer of aluminum in Example 1. Production steps of the present example will be described specifically. (Step 1: step of forming the lower electrodes of metal on the substrate)

The substrate 1 was prepared by depositing SiO_2 in the thickness of 1 μm on soda lime glass and then the substrate 1 was washed well with detergent, pure water, and organic solvent or the like. The material Pt for the lower electrode was deposited in the thickness of 500 nm on the substrate by sputtering and thereafter the lower electrode wires 71 were formed in stripes on the substrate 1 by the photolithography technology.

(Step 2: step of forming the insulating layer)

Next, SiO_2 was deposited in the thickness of 50 nm by sputtering.

(Step 3: step of forming the upper electrode on the insulating layer)

The upper electrode 72 was made of Pt in the thickness of 10 nm in the same manner as the lower electrodes were.

(Step 4: step of forming the pores in the insulating layer)

In the stack structure of lower electrode / SiO_2 / upper electrode as described above, four types of pores were formed as follows by the focused ion beam method; (the diameter 50 nm and the pitch 100 nm of the pores), (the diameter 200 nm and the pitch 400 nm of the pores), (the diameter 500 nm and the pitch 1000 nm of the pores), and (the diameter 1000 nm and the pitch 2000 nm of the pores). Here, the pitch is a distance between centers of adjacent pores.

(Step 5: step of forming carbon in the pores of the insulating layer (under existence of organic material of gas shape))

The substrate 1 was set in the vacuum chamber also serving as a measuring device and the voltage was applied to the upper electrode and lower electrode under an ambience containing gas of acetone at 10^{-2} Pa. The rectangular waves of the voltage waveform having the pulse width T1 of 1 ms and the pulse spacing T2 of 10 ms in the pulse waveform of Fig. 6A were applied for fifteen minutes and then the lower electrode side was kept at the higher potential for five minutes.

(Step 6: stabilization step)

Then the acetone gas was exhausted sufficiently and thereafter the system was evacuated for two hours while being heated at 300 °C.

Then the substrate was set in the vacuum process system of Fig. 5 and the voltage was applied to the lower electrode and upper electrode of each device, and to the anode electrode to measure the currents (the device current and emission current), and the device voltage characteristics.

The electron emission efficiency was dependent upon the diameter of the pores as illustrated in Fig. 31, and the electron emission efficiency increased with decreasing diameter of pore.

[Example 4 of the fourth embodiment]

The present example is an example of application to the image pickup device of Figs. 9A and 9B described previously, in which a plurality of electron-emitting devices prepared by the same method as in Example 1 of the fourth embodiment are placed in a two-dimensional array on the substrate.

The production method of the image pickup device of the present example is the same as in the first embodiment. The image pickup device produced in this way was operated based on the principle of operation stated previously, whereupon the signal current was obtained in 1:1 correspondence to the size of the electron-emitting device, thereby verifying the operation.

[Example 5 of the fourth embodiment]

The present example is an example of

construction of the display device of Figs. 10A and 10B described previously, in which a plurality of electron-emitting devices produced by the same method as in Example 1 of the fourth embodiment are arrayed in a two-dimensional pattern on the substrate. The production method of the display device of the present example is the same as in the first embodiment. The display device produced in this way was operated based on the principle of operation discussed previously, and a bright image was displayed in high definition.

According to the present invention in the first embodiment as described above, the electron-emitting device is constructed in such structure that the insulating layer having the pores formed by anodic oxidation or the like is provided on the lower electrode, at least carbon is formed in the pores, and the gap is given between the carbon and the upper electrode; therefore, when the voltage is applied between the lower electrode and the upper electrode so as to establish the higher potential on the upper electrode, the electrons injected from the lower electrode tunnel into the vacuum to be emitted. Since the distance of the gap between the carbon formed from the lower electrode, and the upper electrode is nearly constant, the characteristics of the electron-emitting device with little variation can be obtained without dependence of the driving voltage on the thickness of

the insulating layer, different from the conventional MIM electron-emitting devices. Since the electron-emitting bodies grown from the lower electrode side is of at least one of graphite, amorphous carbon, and diamondlike carbon, the device is produced with excellent heat resistance and with stable electron emission characteristics in good repeatability. Since the pores are formed in high density and further on the regular basis, the electron-emitting device can be obtained with large emission current and with high efficiency. The spread of the electron beam is decreased and the electron beam equivalent to the formation region of electron emitting device can be formed depending upon conditioning. When an electron source is constructed by placing a plurality of such electron-emitting devices of the present invention, the stable electron source can be provided with little variation from the above reasons. When the electron source is constructed in such structure that the plurality of electron-emitting devices thus placed are located at intersecting portions between the upper wires electrically connected to the upper electrodes and the lower wires electrically connected to the lower electrodes and that the upper wires and the lower wires are arranged nearly perpendicular to each other, a specific electron-emitting device can be selected and modulated out of the plurality of electron-emitting

devices, by the voltage applied to an upper wire and a lower wire thereof. An image pickup device with high resolution and with excellent uniformity can be provided with little variation by combining the above
5 electron source with a photoconductive member disposed opposite to the electron source. Further, a display device with high definition and with excellent uniformity can be provided with little variation by combining the above electron source of the present
10 invention with an image forming member disposed opposite to the electron source.

According to the present invention in the second embodiment, the electron-emitting device is constructed in such structure that on the substrate
15 there are the lower electrode, the insulating layer having the pores, and the upper electrode stacked in this order, the insulating layer has the pores, and the electron-emitting regions are provided in the pores, wherein each electron-emitting region is comprised of
20 the small gaps between the lower electrode and the upper electrode and wherein each small gap is formed by the conductive body formed along the inner wall of pore and the upper electrode; therefore, when the voltage is applied between the lower electrode and the upper
25 electrode so as to place the higher potential on the upper electrode, the electrons from the lower electrode tunnel through the gap between the lower electrode and

the upper electrode into the vacuum and the electrons are efficiently emitted without being affected by the potential of the conductive body formed along the inner wall of pore. In addition, because the distance from the small gap to the top surface of the upper electrode is not more than 200 nm, the electrons colliding with and scattered by the upper electrode do not undergo repetitive scattering, thereby increasing the electron emission efficiency. Since the length of the pores is not more than 500 nm, the singular point of the electric field is constricted even by the potential of the upper electrode of the lower voltage, thereby increasing the electron emission efficiency. Since the distance of the gap between the conductive body formed along the inner wall of pore on the lower electrode, and the upper electrode is determined by the carbon material formed and the voltage applied and is almost constant, the characteristics of the electron-emitting device with little variation can be obtained without dependence of the driving voltage on the thickness of the insulating layer, unlike the conventional MIM electron-emitting devices. Since the electron-emitting bodies of the conductive material grown from the lower electrode side are of at least either one of graphite, amorphous carbon, and diamondlike carbon, the device can be produced with excellent heat resistance and with stable electron emission characteristics in good

repeatability. The conductive bodies may be constructed in such structure that a conductive body of columnar metal or the like is preliminarily formed in each pore and rim-shape carbon is further formed along the inner wall of pore on the columnar metal. In this case, the insulating layer can be made thicker, and the capacitance is thus lowered of the insulating layer between the upper electrode and the lower electrode, which is advantageous in driving of the electron-emitting device. Since the pores can be formed in high density and on the regular basis, the efficient electron-emitting device can be obtained with large emission current. Since emission of electrons from the conductive electron-emitting bodies formed in the pores mainly occurs from the linear electron-emitting bodies of the rim shape, the electron-emitting region can be increased drastically, as compared with the small region at the cone tip in the conventional field emission devices. While the conventional surface conduction electron-emitting devices have the one-dimensional or linear electron-emitting region, the electron-emitting region of the present invention can be formed two-dimensionally and can thus be increased drastically. Accordingly, the emission current density (a ratio of emission current to electron emission area) is decreased, whereby degradation can be suppressed of the characteristics of the electron-emitting device.

When compared with the conventional field emission devices, the spread of electron beam is decreased and the electron beam equivalent to the formation region of the electron-emitting device can be formed depending upon the conditions. When an electron source is constructed by arraying a plurality of such electron-emitting devices of the present invention, the stable electron source can be provided with little variation from the above reasons. When the electron source is constructed in such structure that the plurality of electron-emitting devices thus arranged are located at intersecting points between the upper wires electrically connected to the upper electrodes and the lower wires electrically connected to the lower electrodes or that each device is located near each intersecting point and the upper wires and the lower wires are arranged nearly perpendicular to each other, a specific electron-emitting device can be selected and modulated out of the plurality of electron-emitting devices, by the voltage applied to an upper wire and a lower wire thereof. When the electron-emitting devices are not located at the intersecting points between the upper wires and the lower wires, but are located near the intersecting points, degrees of freedom are increased for design of wires and devices. Namely, the size of device can be selected so as to match with a necessary emitted electron amount. The degrees of

freedom of design are also increased, because the decrease of the capacitance at the intersecting point between wires separates the size from the device size designed from the necessary electron emission amount of device. An image pickup device with high resolution and with excellent uniformity can be provided with little variation by combining the above electron source with a photoconductive member disposed opposite to the electron source. Further, an image forming apparatus with high definition and with excellent uniformity can be provided with little variation by combining the above electron source of the present invention with an image forming member disposed opposite to the electron source.

According to the present invention in the third embodiment, the electron-emitting device is constructed in such structure that on the substrate there are the lower electrode, the insulating layer having the pores, and the upper electrode stacked in this order, the insulating layer has the pores, and the electron-emitting bodies are provided in the pores, wherein, with the thickness t of the upper electrode, the length L of the pores, and the mean free path λ of electron transmission of the upper electrode, the device satisfies the condition of $0.5 \times L \leq t < 2\lambda$; therefore, when the voltage is applied between the lower electrode and the upper electrode so as to establish the higher

potential on the upper electrode, the electrons injected from the lower electrode tunnel from the electron-emitting bodies into the vacuum, further pass through the upper electrode, and fly to the anode plate. Since the thickness of the upper electrode is not less than $0.5 \times L$ where L is the length of the pores, the upper electrode can cover the apertures of the pores. Since the thickness of the upper electrode is not more than 2λ where λ is the mean free path of electron transmission of the upper electrode, the emitted electrons can efficiently pass through the upper electrode to reach the anode plate. Since the space between the electron-emitting bodies and the upper electrode is the vacuum with small dielectric constant, scattering of electron due to the insulating layer does not occur, when compared with the MIM type provided with the insulating layer, and loss of emitted electrons is thus decreased. Further, the electric capacitance is lowered considerably, which is advantageous in driving of the electron-emitting device, e.g., in power consumption. Since the electron-transmitting portions of the upper electrode have the large mean free path of electron transmission and are of the carbon material having at least either one of graphite, amorphous carbon, and diamondlike carbon with excellent electron transmittance, the emitted electrons efficiently pass through the upper

electrode to reach the anode electrode. Since carbon is a material with high heat resistance, there occurs little degradation during driving of the electron-emitting device, whereby stability is enhanced. Since
5 the carbon material is bound by covalent bond, the shape of the upper electrode covering the regions above the pores can be implemented easier than the metal electrode. In the case of the electron-emitting device of the present invention where the electron-emitting
10 bodies are the needlelike electrodes deposited on the lower electrode or the small particles deposited on the lower electrode, the local electric field is large and the driving voltage is decreased because of the pores, thereby lowering power consumption. In the case of the
15 electron-emitting device of the present invention where the electron-emitting bodies are the rim-shape conductive bodies formed along the inner walls of the pores or the columnar conductive bodies formed in the pores and where there is the small gap between the
20 electron-emitting bodies and the upper electrode, the driving voltage is low because of the small gap and the capacitance is lowered because of the vacuum. Further, where the conductive bodies of the columnar shape are provided between the electron-emitting bodies and the
25 lower electrode, the thickness of the insulating layer can be separated from the electron emission field and the thickness of the insulating layer can thus be made

larger. This can decrease the capacitance between the upper electrode and the lower electrode, which is advantageous in driving. Since the pores can be formed in high density and on the regular basis, the efficient
5 electron-emitting device can be obtained with large emission current. Since the device is driven at the low emission current density (the ratio of emission current to electron emission area) in practical driving, degradation of the characteristics of the
10 electron-emitting device can be suppressed. When the electron-emitting device of the present invention is compared with the conventional field emission devices having the apertures in the upper electrode above the pores, the device of the invention has the upper
15 electrode above the pores as well; therefore, the spread of electron beam is decreased and the electron beam equivalent to that by the MIM device can be formed. When an electron source is constructed by arraying a plurality of such electron-emitting devices
20 of the present invention, the stable electron source can be provided with high definition from the above reasons. When the electron source is constructed in such structure that the plurality of electron-emitting devices thus arranged are located at intersecting
25 points between the upper wires electrically connected to the upper electrodes and the lower wires electrically connected to the lower electrodes or that

each device is located near each intersecting point and the upper wires and the lower wires are arranged nearly perpendicular to each other, a specific electron-emitting device can be selected and modulated out of the plurality of electron-emitting devices, by the voltage applied to an upper wire and a lower wire thereof. When the electron-emitting devices are not located at the intersecting points between the upper wires and the lower wires, but are located near the intersecting points, degrees of freedom are increased for design of wires and devices. Namely, the size of device can be selected so as to match with a necessary emitted electron amount. The degrees of freedom of design are also increased, because the decrease of the capacitance at the intersecting point between wires separates the size from the device size designed from the necessary electron emission amount of device. An image pickup device with high resolution and with excellent uniformity can be provided with little variation by combining the above electron source with a photoconductive member disposed opposite to the electron source. Further, an image forming apparatus with high definition and with excellent uniformity can be provided with little variation by combining the above electron source of the present invention with an image forming member disposed opposite to the electron source.

According to the present invention in the fourth embodiment, the electron-emitting device is constructed in such structure that on the substrate there are the lower electrode, the insulating layer
5 having the pores, and the upper electrode stacked in this order, the insulating layer has the pores, and the electron-emitting regions are provided in the pores, wherein each electron-emitting regions is comprised of the small gap between the lower electrode and upper
10 electrode and wherein the distance from the small gap to the top surface of the upper electrode is not more than 200 nm; therefore, when the voltage is applied between the lower electrode and the upper electrode so as to establish the higher potential on the upper
15 electrode, the electrons injected from the lower electrode tunnel through the gap between the lower electrode and the upper electrode into the vacuum to be emitted. Further, the electrons colliding with and scattered by the upper electrode do not undergo
20 repetitive scattering, thereby increasing the electron emission efficiency. Since the length of the pores is not more than 500 nm, the singular point of the electric field is constricted even by the potential of the upper electrode of the lower voltage, thereby
25 increasing the electron emission efficiency. Since the distance of the gap between the conductive bodies formed on the lower electrode, and the upper electrode

is determined by the carbon material formed and the voltage applied and is almost constant, the characteristics of the electron-emitting device with little variation can be obtained without dependence of the driving voltage on the thickness of the insulating layer, unlike the conventional MIM type electron-emitting devices. Since the electron-emitting bodies of the conductive bodies of the columnar shape grown from the lower electrode are of at least either one of graphite, amorphous carbon, and diamondlike carbon, the device can be produced with excellent heat resistance and with stable electron emission characteristics in high repeatability. The conductive bodies may be of a stack of the columnar metal and carbon in which the metal is preliminarily formed in the pores and then carbon is formed. In this case, the insulating layer can be made thicker, so that the capacitance is lowered of the insulating layer between the upper electrode and the lower electrode, which is advantageous in driving of the electron-emitting device. Since the pores can be formed in high density and on the regular basis, the efficient electron-emitting device can be obtained with large emission current. Since the electrons from the electron-emitting bodies formed in the pores are emitted mainly from the periphery of the electron-emitting bodies of the columnar shape, the electron-emitting region can be increased drastically, as

compared with the small region at the cone tip in the conventional field emission devices. As compared with the conventional surface conduction electron-emitting devices, the electron-emitting region can be increased
5 largely, because it can be formed two-dimensionally. Accordingly, the emission current density (the ratio of emission current to electron emission area) is decreased, so that degradation of the characteristics of the electron-emitting device can be suppressed. In
10 the electron-emitting device of the present invention the spread of electron beam is decreased, as compared with the conventional field emission devices. When an electron source is constructed by arraying a plurality of such electron-emitting devices of the present
15 invention, the stable electron source can be provided with little variation from the above reasons. When the electron source is constructed in such structure that the plurality of electron-emitting devices thus arranged are located at intersecting points between the
20 upper wires electrically connected to the upper electrodes and the lower wires electrically connected to the lower electrodes or that each device is located near each intersecting point and the upper wires and the lower wires are arranged nearly perpendicular to
25 each other, a specific electron-emitting device can be selected and modulated out of the plurality of electron-emitting devices, by the voltage applied to an

upper wire and a lower wire thereof. When the electron-emitting devices are not located at the intersecting points between the upper wires and the lower wires, but are located near the intersecting points, degrees of freedom are increased for design of wires and devices. Namely, the size of device can be selected so as to match with a necessary emitted electron amount. The degrees of freedom of design are also increased, because the decrease of the capacitance at the intersecting point between wires separates the size from the device size designed from the necessary electron emission amount of device. An image pickup device with high resolution and with excellent uniformity can be provided with little variation by combining the above electron source with a photoconductive member disposed opposite to the electron source. Further, an image forming apparatus with high definition and with excellent uniformity can be provided with little variation by combining the above electron source of the present invention with an image forming member disposed opposite to the electron source.

WHAT IS CLAIMED IS:

1. An electron-emitting device comprising a lower electrode, an insulating layer having a pore, and an upper electrode stacked in this order on a
5 substrate,

wherein a carbon deposit is provided in said pore, and a small gap is provided between said upper electrode and said carbon deposit.

10 2. The electron-emitting device according to Claim 1, wherein said insulating layer is an anodic oxide layer.

3. The electron-emitting device according to
15 Claim 1, wherein said carbon deposit is electrically conductive and is electrically connected to said lower electrode.

4. The electron-emitting device according to
20 Claim 1, wherein said carbon deposit is electrically conductive and an insulator is interposed between said lower electrode and said carbon deposit.

5. The electron-emitting device according to
25 Claim 1, wherein said carbon deposit is of a polelike shape.

6. The electron-emitting device according to Claim 1, wherein said upper electrode exists in a region except for a region above the pore of an anodic oxide layer.

5

7. The electron-emitting device according to Claim 1, wherein said carbon deposit is electrically conductive and is electrically connected to said upper electrode.

10

8. The electron-emitting device according to Claim 7, wherein a gap is provided between the carbon deposit on said lower electrode and the carbon deposit connected to said upper electrode.

15

9. An electron-emitting device comprising a lower electrode, an insulating layer having a pore, and an upper electrode stacked in this order on a substrate,

20

wherein an electron-emitting region is provided in said pore, said electron-emitting region being comprised of a small gap between said lower electrode and upper electrode, said small gap being formed by an electroconductive body of a rim shape formed along an inner wall of said pore, and the upper electrode.

25

10. The electron-emitting device according to

Claim 9, wherein said insulating layer is an anodic oxide layer.

11. The electron-emitting device according to
5 Claim 9, wherein said electroconductive body formed along the inner wall of the pore is formed on an electroconductive body of a polelike shape formed in said pore.

10 12. The electron-emitting device according to Claim 9, wherein said electroconductive body formed along the inner wall of the pore is a carbon deposit.

13. The electron-emitting device according to
15 Claim 11, wherein said electroconductive body of the polelike shape is metal.

14. The electron-emitting device according to Claim 9, wherein a distance from said small gap to a
20 top surface of the upper electrode is not more than 200 nm.

15. The electron-emitting device according to Claim 9, wherein a length of said pore is not more than
25 500 nm.

16. The electron-emitting device according to

Claim 9, wherein said small gap is not more than 20 nm.

17. An electron-emitting device comprising a lower electrode, an insulating layer having a pore, and
5 an upper electrode stacked in this order on a substrate,

wherein an electron-emitting body is provided in said pore, and wherein the following condition is satisfied:

10
$$0.5 \times L \leq t < 2\lambda$$

where t is a thickness of said upper electrode, L is a length of said pore, and λ is a mean free path of electron transmission of said upper electrode.

15 18. The electron-emitting device according to Claim 17, wherein said upper electrode has a carbon deposit.

19. The electron-emitting device according to
20 Claim 17, wherein said electron-emitting body is a needlelike electrode deposited on said lower electrode.

20. The electron-emitting device according to Claim 17, wherein said electron-emitting body is a
25 small particle deposited on said lower electrode.

21. The electron-emitting device according to

Claim 17, wherein said electron-emitting body is an
electroconductive body of a rim shape formed along an
inner wall of said pore and a small gap is provided
between the electroconductive body of the rim shape
5 formed along the inner wall of the pore, and the upper
electrode.

22. The electron-emitting device according to
Claim 17, wherein said electron-emitting body is an
10 electroconductive body of a columnar shape formed in
said pore and a small gap is provided between the
electroconductive body of the columnar shape formed in
said pore, and the upper electrode.

15 23. The electron-emitting device according to
Claim 17, wherein said electron-emitting body is formed
on an electroconductive body of a polelike shape formed
in said pore.

20 24. The electron-emitting device according to
Claim 17, wherein said electron-emitting body has a
carbon deposit.

25 25. The electron-emitting device according to
Claim 23, wherein said electroconductive body of the
polelike shape is metal.

26. The electron-emitting device according to Claim 17, wherein said insulating layer is an anodic oxide layer.

5 27. The electron-emitting device according to Claim 17, wherein said electron-emitting body lies on an insulating layer formed on the lower electrode.

28. An electron-emitting device comprising a
10 lower electrode, an insulating layer having a pore, and an upper electrode stacked in this order on a substrate, wherein an electron-emitting region is provided in said pore,

 said electron-emitting region being comprised
15 of a small gap between said lower electrode and upper electrode, and wherein a distance from the small gap to a top surface of the upper electrode is not more than 200 nm.

20 29. The electron-emitting device according to Claim 28, wherein a length of said pore is not more than 500 nm.

30. The electron-emitting device according to
25 Claim 28, wherein said small gap is not more than 20 nm.

31. The electron-emitting device according to Claim 28, wherein said small gap is formed by an electroconductive body of a polelike shape formed in said pore, and the upper electrode.

5

32. The electron-emitting device according to Claim 28, wherein said electroconductive body of the polelike shape is a carbon deposit.

10

33. The electron-emitting device according to Claim 28, wherein said electroconductive body of the polelike shape is metal and carbon.

15

34. The electron-emitting device according to Claim 28, wherein said insulating layer is an anodic oxide layer.

20

35. The electron-emitting device according to Claim 28, wherein said electroconductive body lies on an insulating layer formed on the lower electrode.

25

36. The electron-emitting device according to Claim 1, wherein said pore is of a cylindrical shape having a side face parallel to a direction of emission of electron.

37. The electron-emitting device according to

Claim 9, wherein said pore is of a cylindrical shape having a side face parallel to a direction of emission of electron.

5 38. The electron-emitting device according to Claim 17, wherein said pore is of a cylindrical shape having a side face parallel to a direction of emission of electron.

10 39. The electron-emitting device according to Claim 28, wherein said pore is of a cylindrical shape having a side face parallel to a direction of emission of electron.

15 40. The electron-emitting device according to Claim 1, wherein said carbon deposit is at least one of graphite, amorphous carbon, and diamondlike carbon.

20 41. The electron-emitting device according to Claim 9, wherein said carbon deposit is at least one of graphite, amorphous carbon, and diamondlike carbon.

25 42. The electron-emitting device according to Claim 17, wherein said carbon deposit is at least one of graphite, amorphous carbon, and diamondlike carbon.

43. The electron-emitting device according to

Claim 28, wherein said carbon deposit is at least one of graphite, amorphous carbon, and diamondlike carbon.

44. An electron source comprising a plurality
5 of electron-emitting devices as set forth in Claim 1.

45. An electron source comprising a plurality of electron-emitting devices as set forth in Claim 9.

10 46. An electron source comprising a plurality of electron-emitting devices as set forth in Claim 17.

47. An electron source comprising a plurality of electron-emitting devices as set forth in Claim 28.
15

48. The electron source according to Claim 44, wherein said plurality of electron-emitting devices are located at intersecting points between upper wires electrically connected to upper electrodes and lower
20 wires electrically connected to lower electrodes and wherein said upper wires and said lower wires are arranged perpendicular to each other.

49. The electron source according to Claim 45,
25 wherein said plurality of electron-emitting devices are located at intersecting points between upper wires electrically connected to upper electrodes and lower

wires electrically connected to lower electrodes and wherein said upper wires and said lower wires are arranged perpendicular to each other.

5 50. The electron source according to Claim 46,
wherein said plurality of electron-emitting devices are
located at intersecting points between upper wires
electrically connected to upper electrodes and lower
wires electrically connected to lower electrodes and
10 wherein said upper wires and said lower wires are
arranged perpendicular to each other.

 51. The electron source according to Claim 47,
wherein said plurality of electron-emitting devices are
15 located at intersecting points between upper wires
electrically connected to upper electrodes and lower
wires electrically connected to lower electrodes and
wherein said upper wires and said lower wires are
arranged perpendicular to each other.

20

 52. An image pickup device comprising the
electron source as set forth in Claim 44, and a
photoconductive member disposed opposite to said
electron source.

25

 53. An image pickup device comprising the
electron source as set forth in Claim 45, and a

photoconductive member disposed opposite to said electron source.

54. An image pickup device comprising the
5 electron source as set forth in Claim 46, and a photoconductive member disposed opposite to said electron source.

55. An image pickup device comprising the
10 electron source as set forth in Claim 47, and a photoconductive member disposed opposite to said electron source.

56. An image pickup device comprising the
15 electron source as set forth in Claim 48, and a photoconductive member disposed opposite to said electron source.

57. An image pickup device comprising the
20 electron source as set forth in Claim 49, and a photoconductive member disposed opposite to said electron source.

58. An image pickup device comprising the
25 electron source as set forth in Claim 50, and a photoconductive member disposed opposite to said electron source.

59. An image pickup device comprising the electron source as set forth in Claim 51, and a photoconductive member disposed opposite to said electron source.

5

60. A display device comprising the electron source as set forth in Claim 44, and an image forming member disposed opposite to said electron source.

10

61. A display device comprising the electron source as set forth in Claim 45, and an image forming member disposed opposite to said electron source.

15

62. A display device comprising the electron source as set forth in Claim 46, and an image forming member disposed opposite to said electron source.

20

63. A display device comprising the electron source as set forth in Claim 47, and an image forming member disposed opposite to said electron source.

25

64. A display device comprising the electron source as set forth in Claim 48, and an image forming member disposed opposite to said electron source.

65. A display device comprising the electron source as set forth in Claim 49, and an image forming

member disposed opposite to said electron source.

66. A display device comprising the electron source as set forth in Claim 50, and an image forming member disposed opposite to said electron source.

67. A display device comprising the electron source as set forth in Claim 51, and an image forming member disposed opposite to said electron source.

10

68. A method for producing an electron-emitting device comprising a lower electrode, an insulating layer having a pore, and an upper electrode stacked in this order on a substrate, said electron-emitting device having a carbon deposit in said pore, said method comprising:

15 a step of forming said lower electrode of a metal or a semiconductor on said substrate;

20 a step of forming an anodic oxide layer on a surface of said lower electrode;

a step of producing said carbon deposit in the pore of said anodic oxide layer by applying a voltage under existence of an organic material; and

25 a step of forming the upper electrode.

69. The method for producing the electron-emitting device according to Claim 68, wherein said

organic material is a liquid.

70. A method for producing an electron-emitting device comprising a lower electrode, an
5 insulating layer having a pore, and an upper electrode
stacked in this order on a substrate, said electron-emitting device having a carbon deposit in said pore,
said method comprising:
a step of forming said lower electrode of a
10 metal or a semiconductor on said substrate;
a step of forming an anodic oxide layer in a
surface of said lower electrode;
a step of forming said upper electrode on said
anodic oxide layer in said lower electrode; and
15 a step of producing a carbon deposit in said
pore of said anodic oxide layer by applying a voltage
to said upper electrode and said lower electrode, under
existence of an organic material.

20 71. The method for producing the electron-emitting device according to Claim 70, wherein said
organic material is a gas.

25 72. The method for producing the electron-emitting device according to Claim 68, wherein said
voltage is a pulse-shaped voltage.

73. The method for producing the electron-emitting device according to Claim 70, wherein said voltage is a pulse-shaped voltage.

5 74. The method for producing the electron-emitting device according to Claim 68, wherein on the occasion of applying said voltage, said lower electrode is kept at a higher potential.

10 75. The method for producing the electron-emitting device according to Claim 70, wherein on the occasion of applying said voltage, said lower electrode is kept at a higher potential.

15 76. The method for producing the electron-emitting device according to Claim 68, wherein on the occasion of applying said voltage, a higher potential and a lower potential are alternately applied to said lower electrode.

20 77. The method for producing the electron-emitting device according to Claim 70, wherein on the occasion of applying said voltage, a higher potential and a lower potential are alternately applied to said
25 lower electrode.

78. The method for producing the electron-

emitting device according to Claim 68, wherein said carbon deposit is at least one of graphite, amorphous carbon, and diamondlike carbon.

- 5 79. The method for producing the electron-emitting device according to Claim 70, wherein said carbon deposit is at least one of graphite, amorphous carbon, and diamondlike carbon.

ABSTRACT OF THE DISCLOSURE

An electron-emitting device disclosed has stable electron emission characteristics with little variation, in high electron emission efficiency, in
5 high definition, and at low driving voltage. The electron-emitting device disclosed is constructed in such structure that on a substrate there are a lower electrode, an insulating layer having pores, and an upper electrode stacked in this order, the insulating
10 layer is an anodic oxide layer, and a carbon deposit is formed in the pores.

FIG. 1A

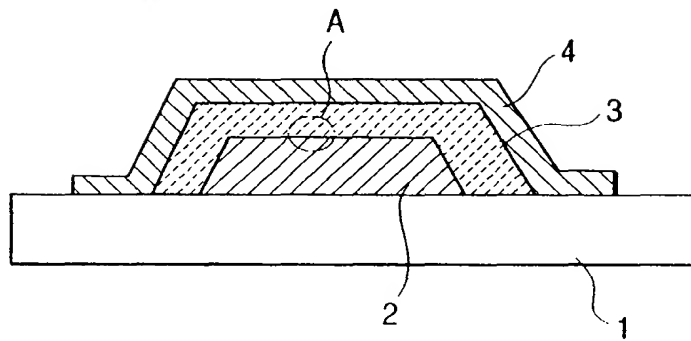


FIG. 1B

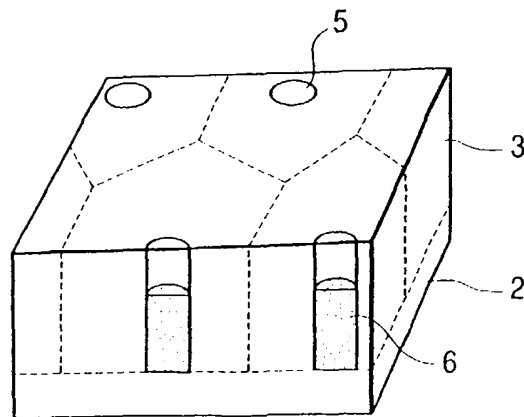


FIG. 2A

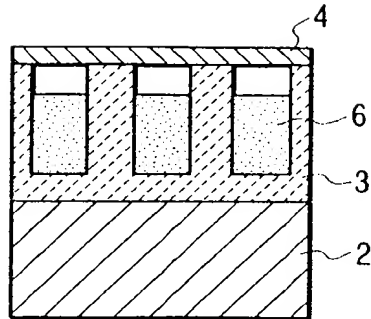


FIG. 2B

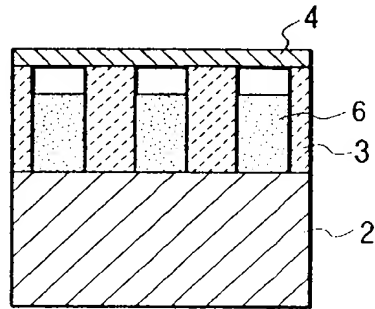


FIG. 2C

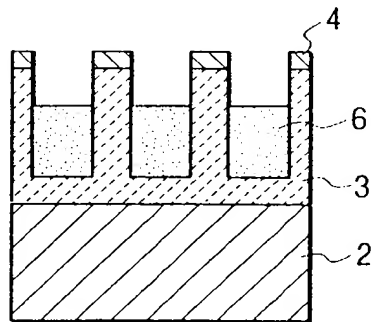


FIG. 2D

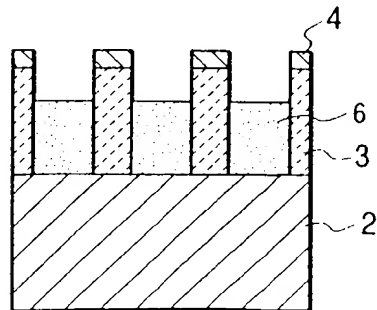


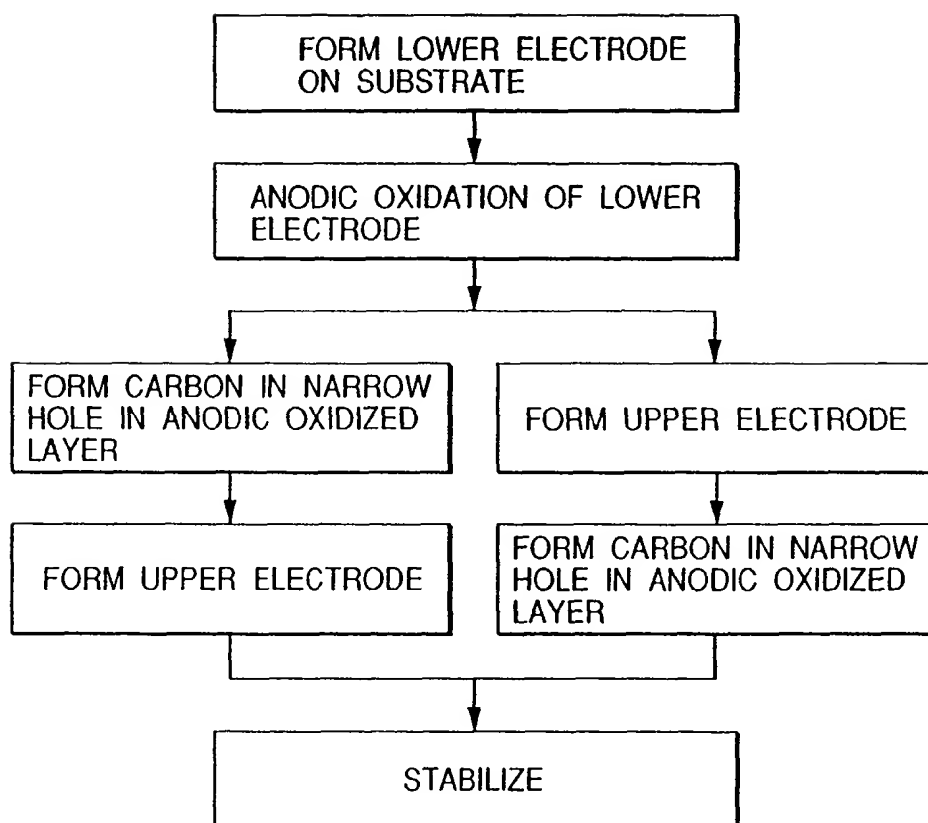
FIG. 3

FIG. 4

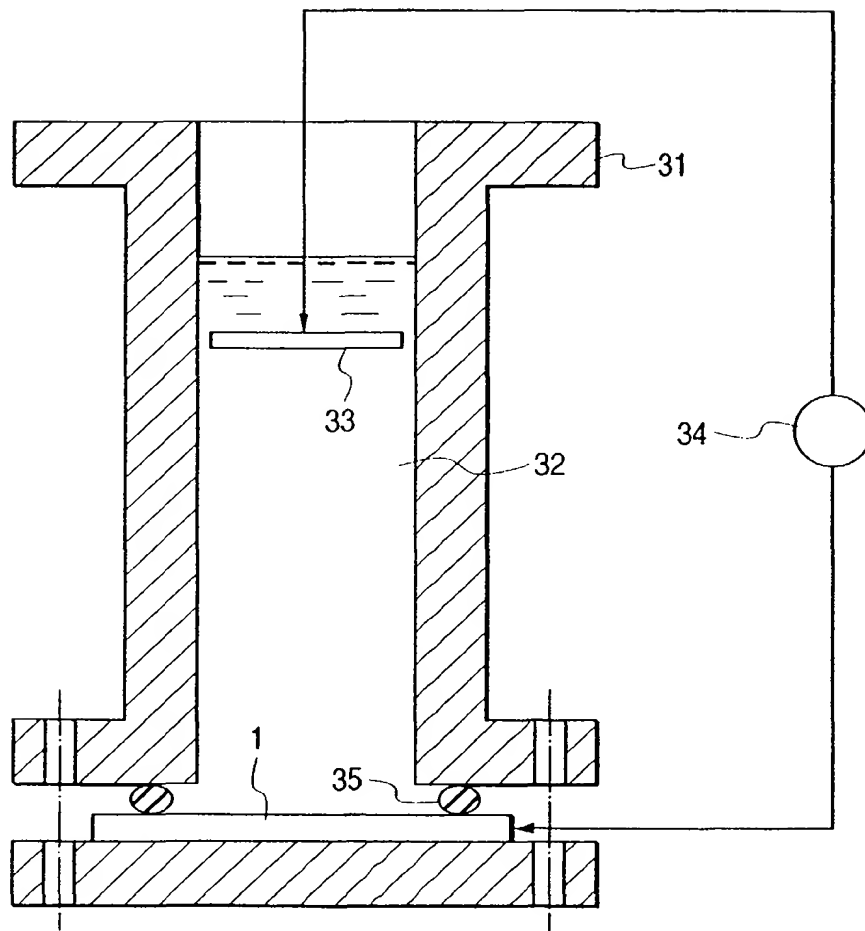


FIG. 5

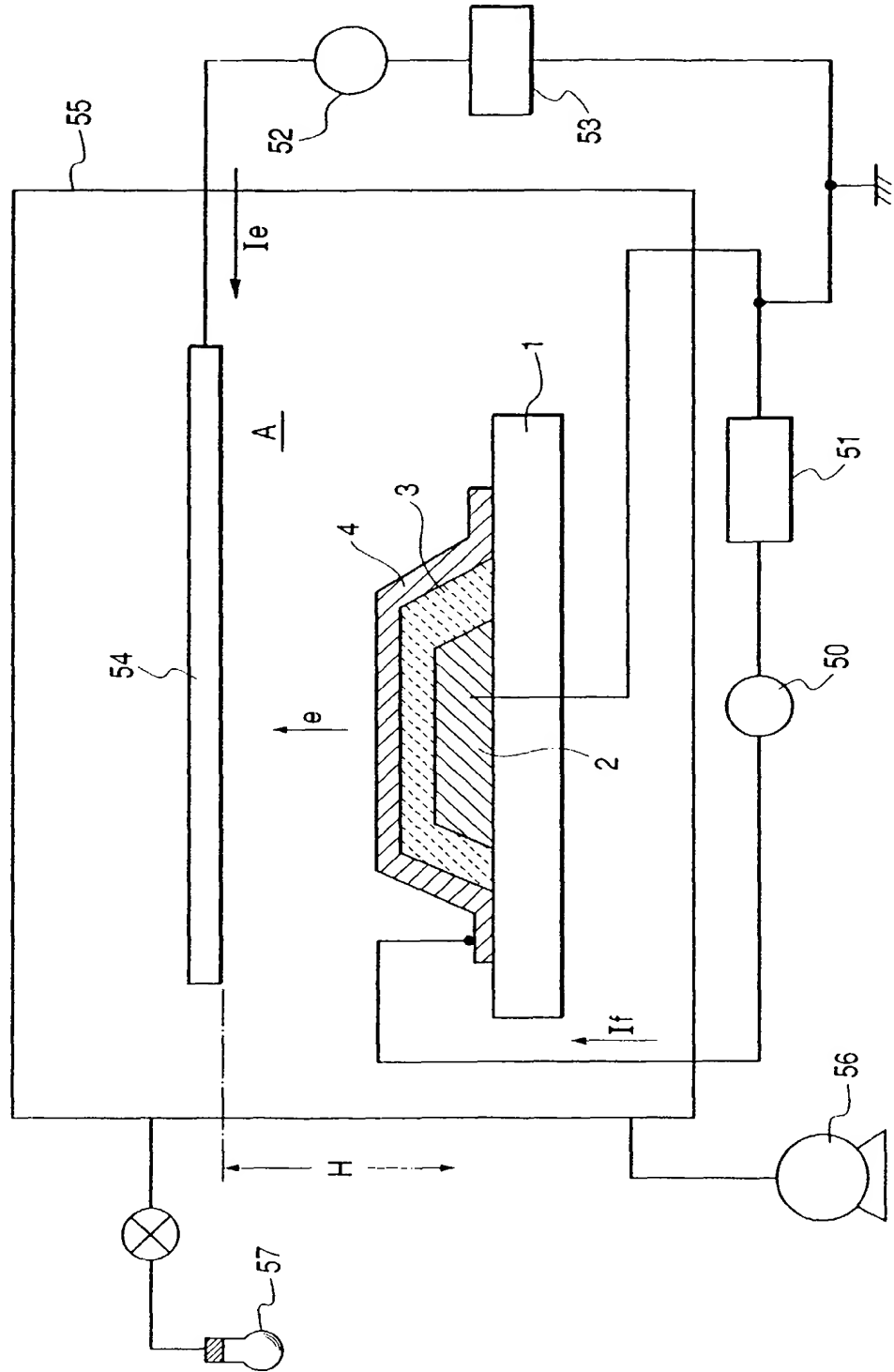


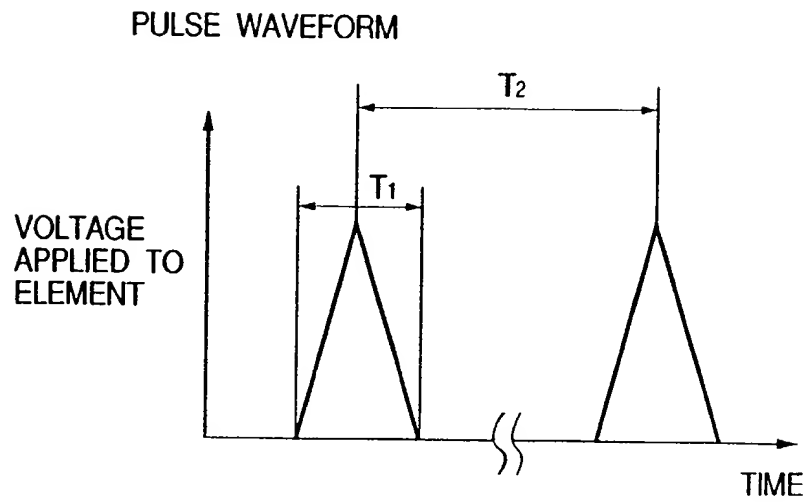
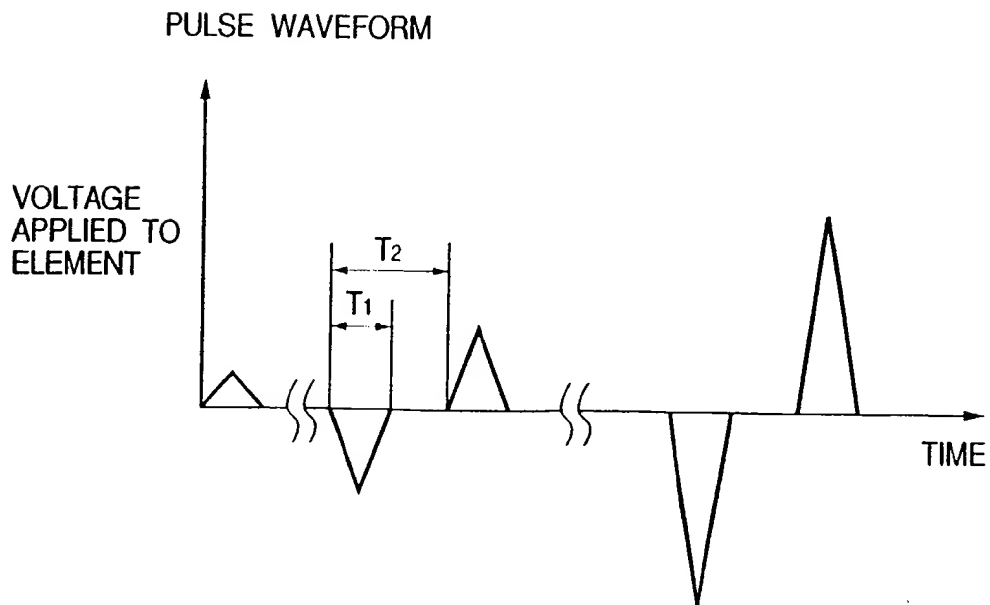
FIG. 6A*FIG. 6B*

FIG. 7A

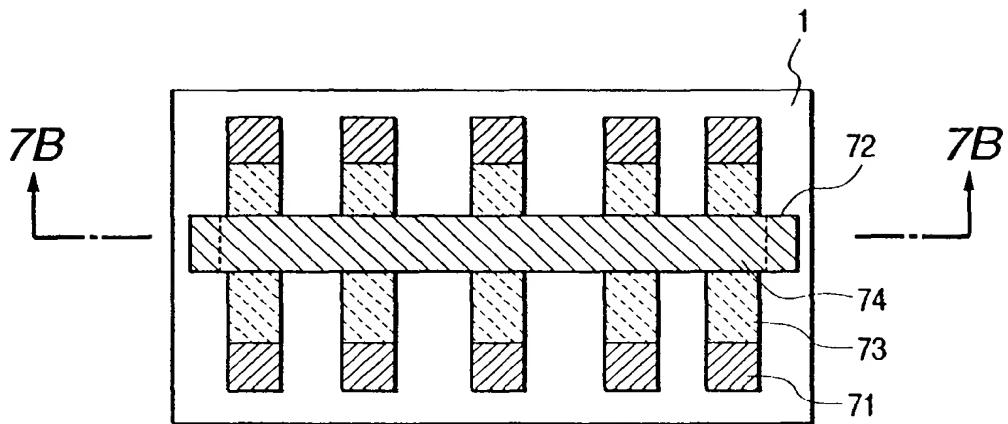


FIG. 7B

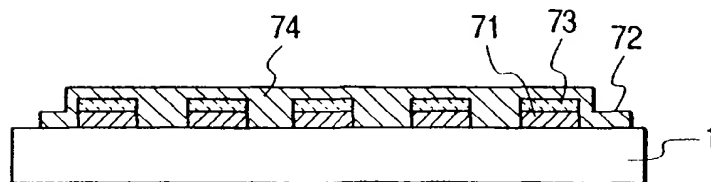


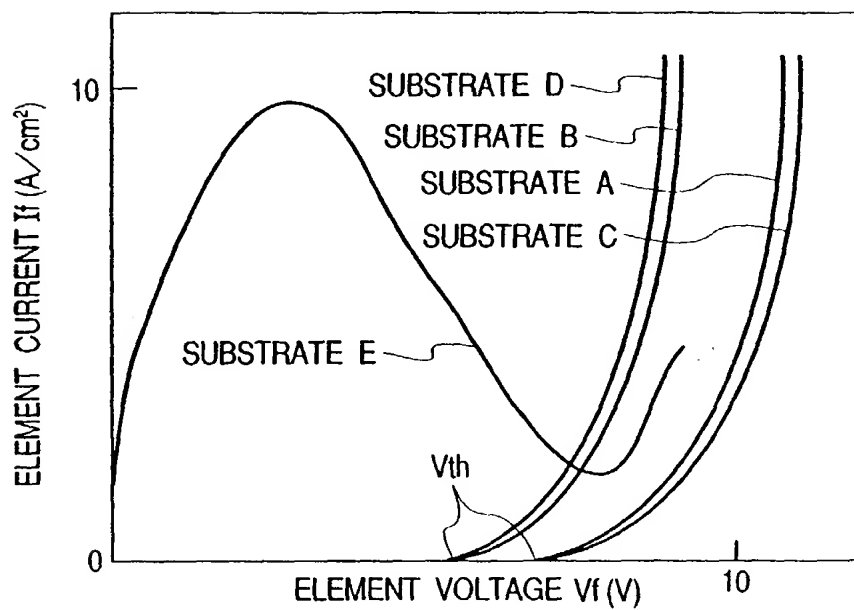
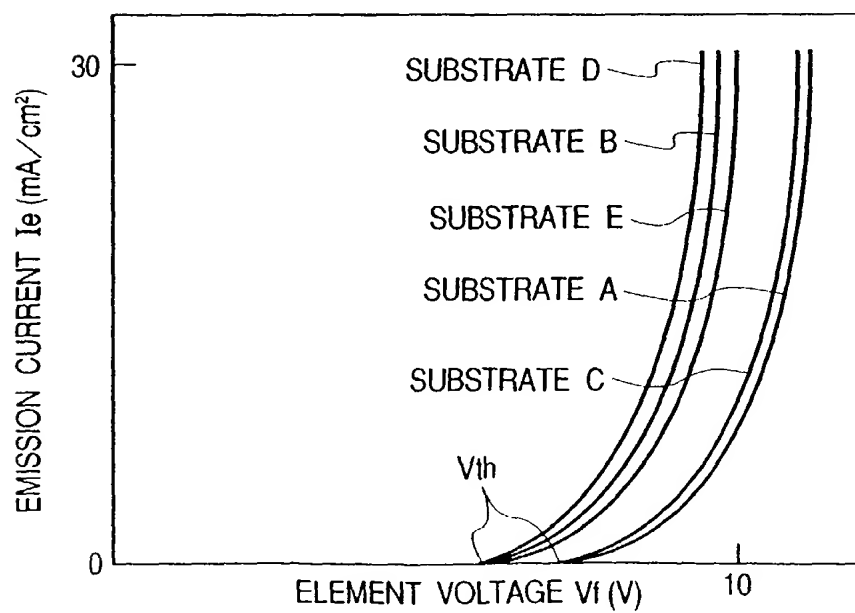
FIG. 8A**FIG. 8B**

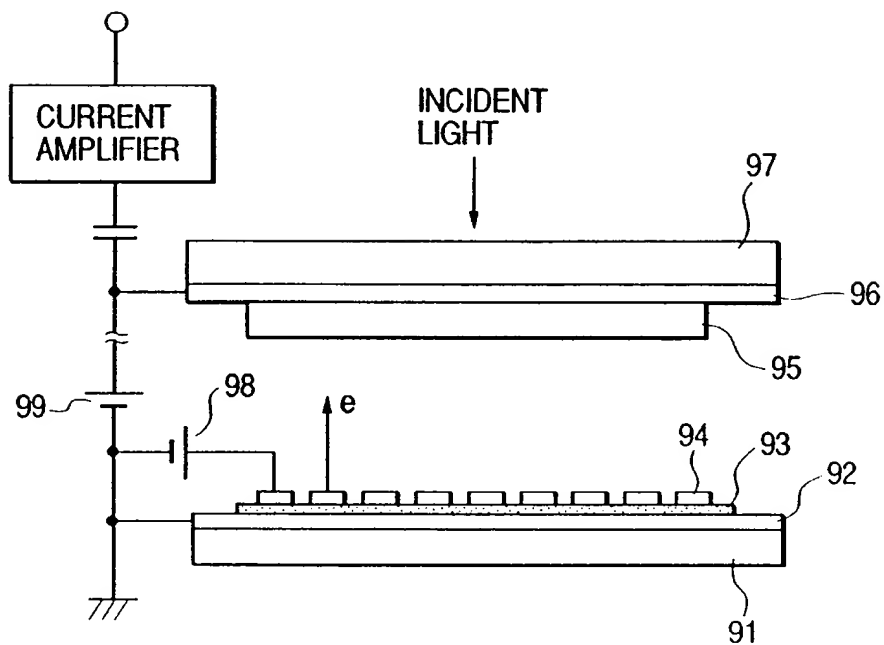
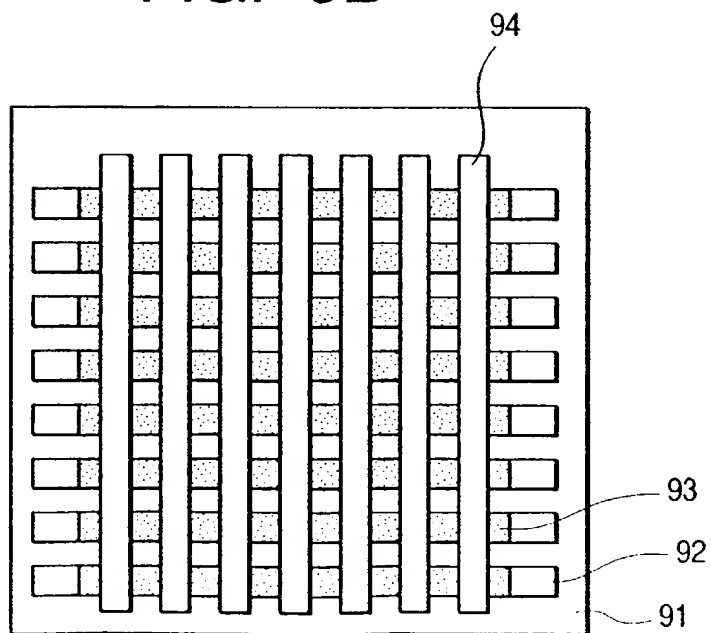
FIG. 9A*FIG. 9B*

FIG. 10A

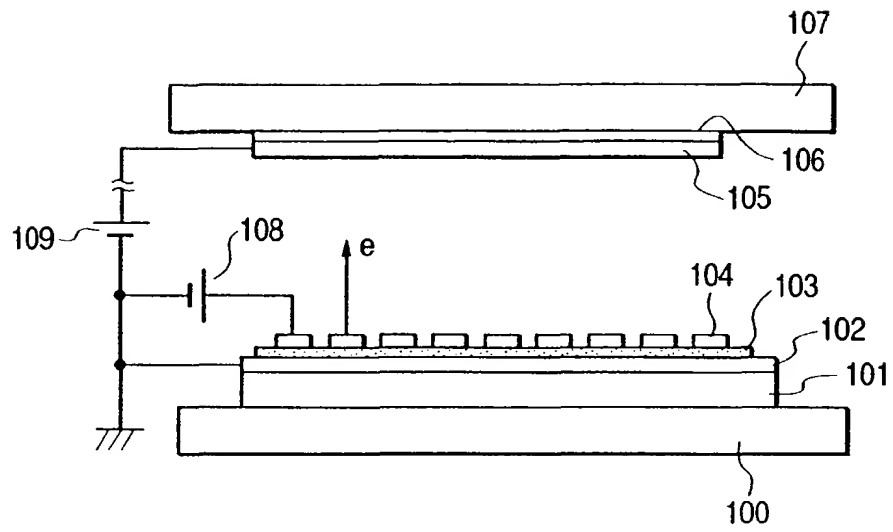


FIG. 10B

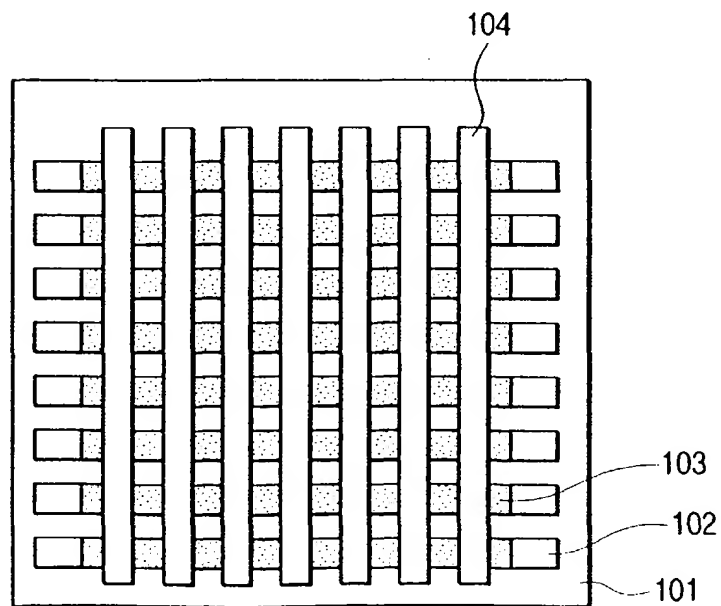


FIG. 11A

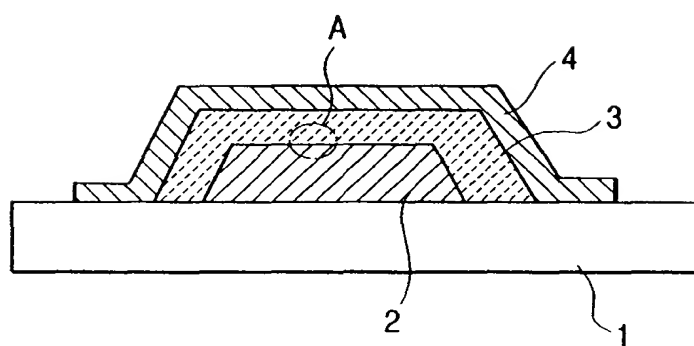


FIG. 11B

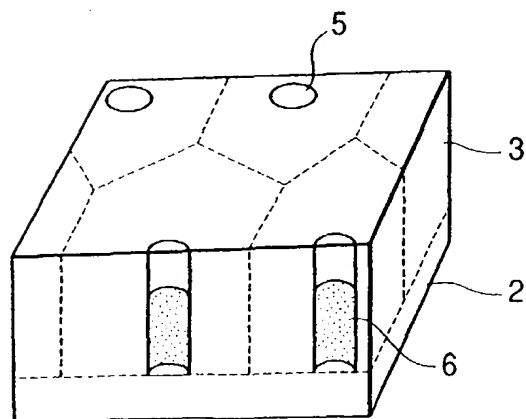


FIG. 12A

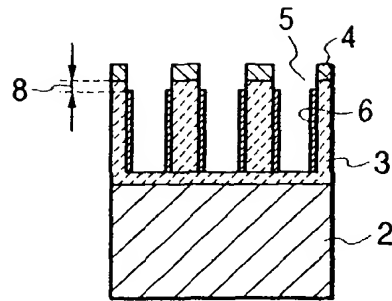


FIG. 12B

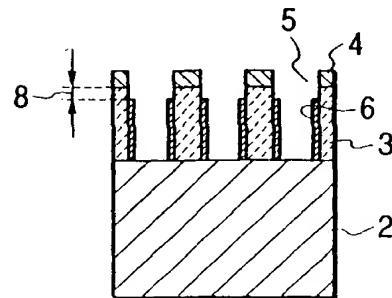


FIG. 12C

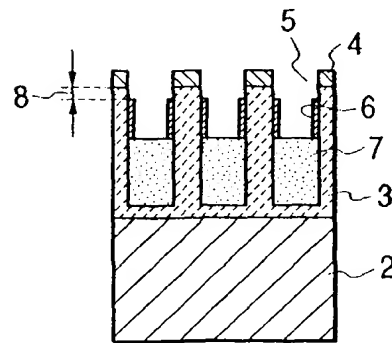


FIG. 12D

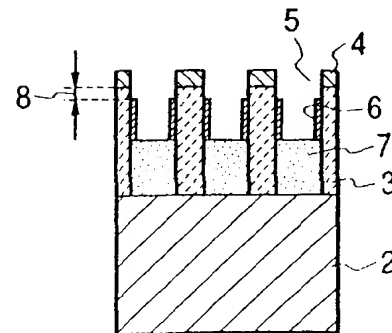


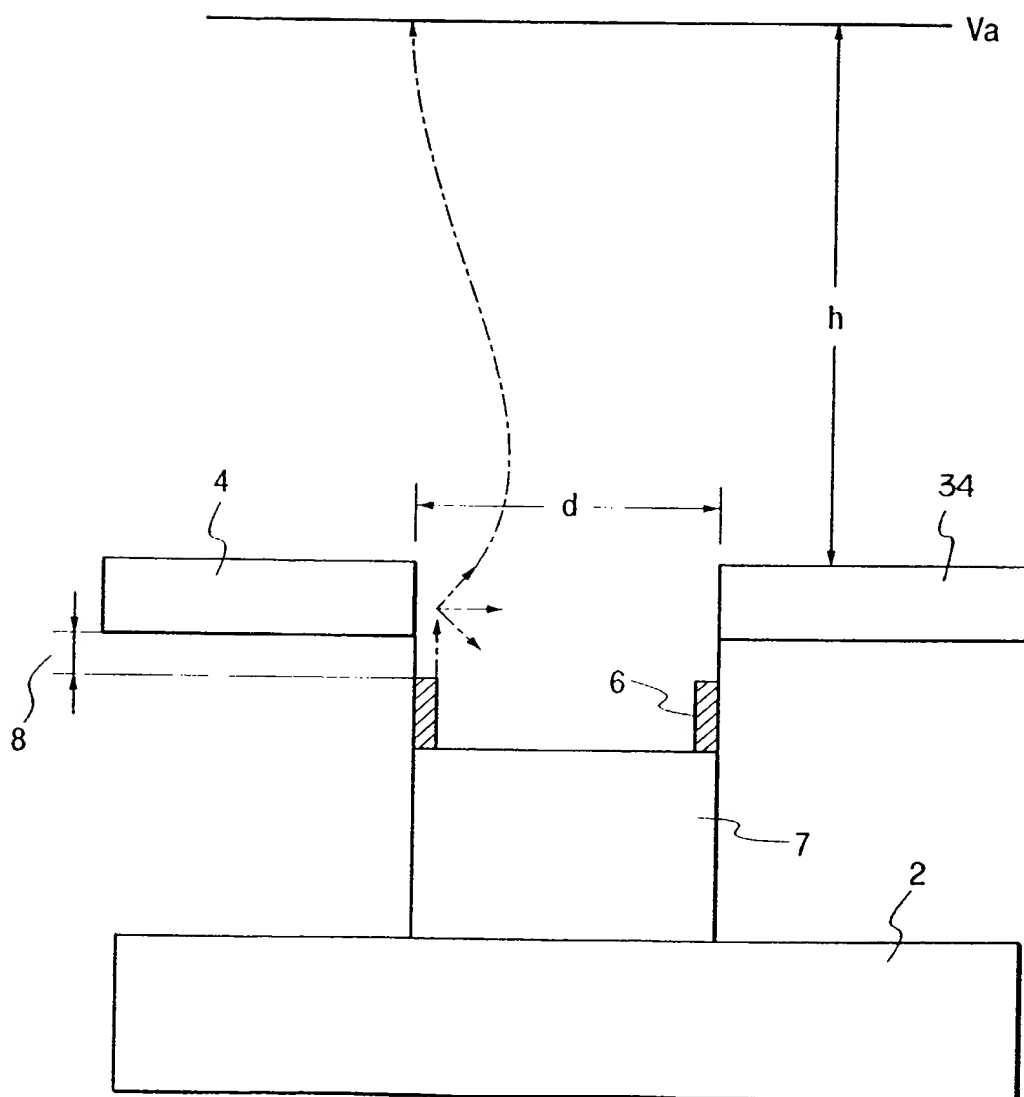
FIG. 13

FIG. 14

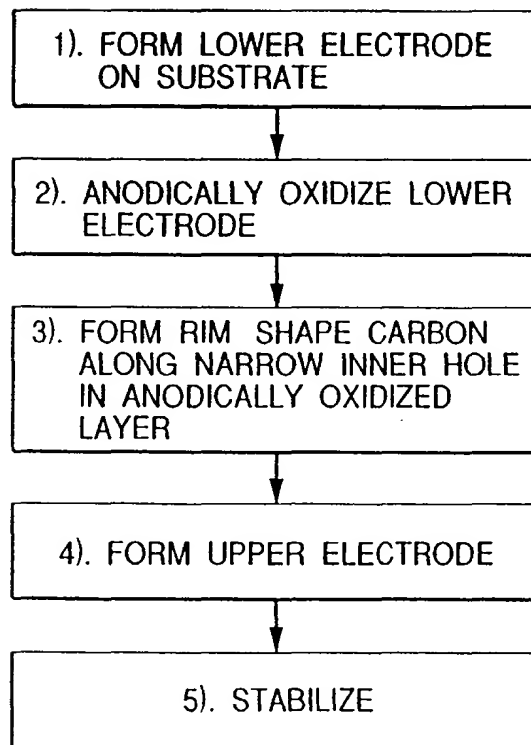


FIG. 15

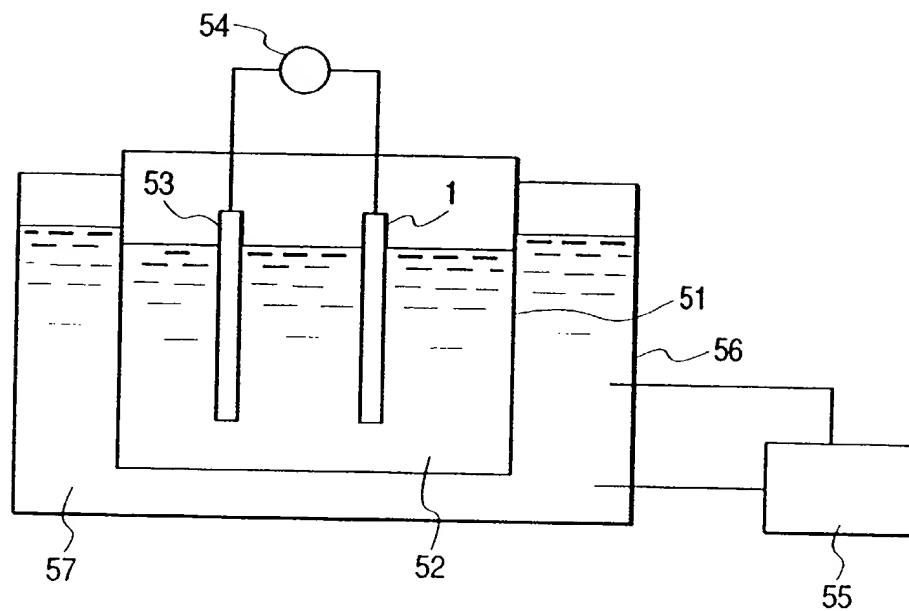


FIG. 16

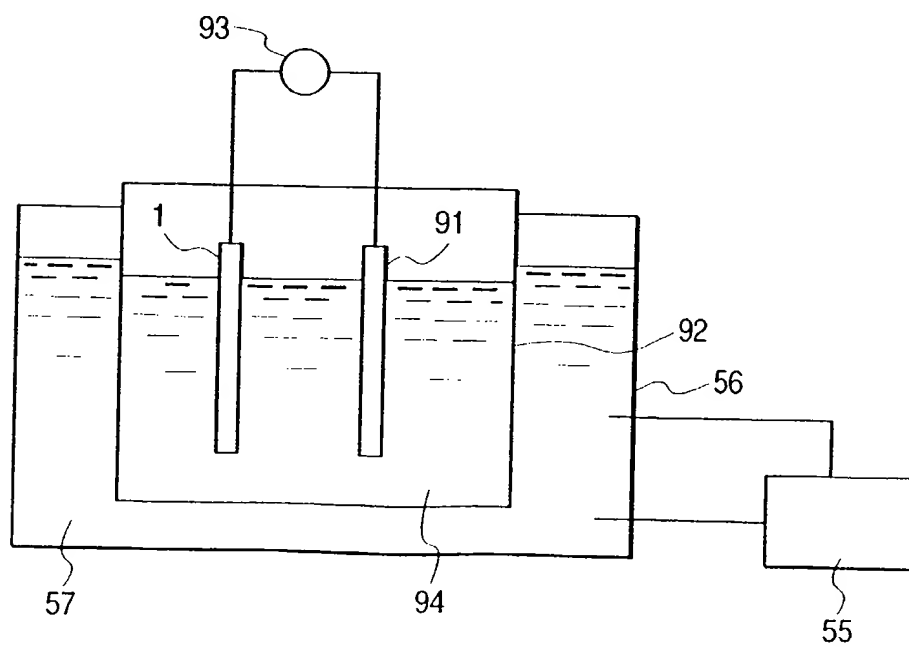


FIG. 17A

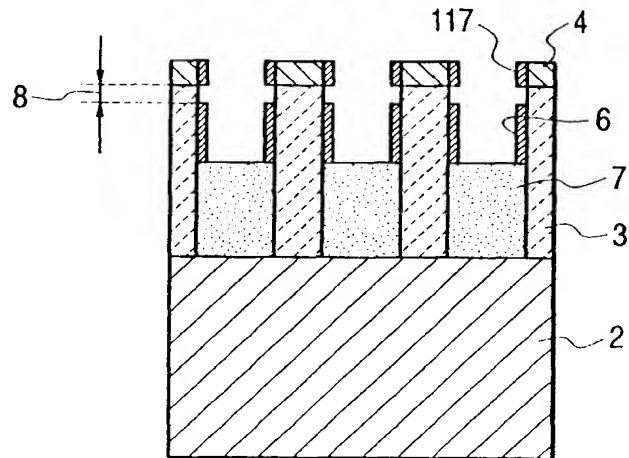


FIG. 17B

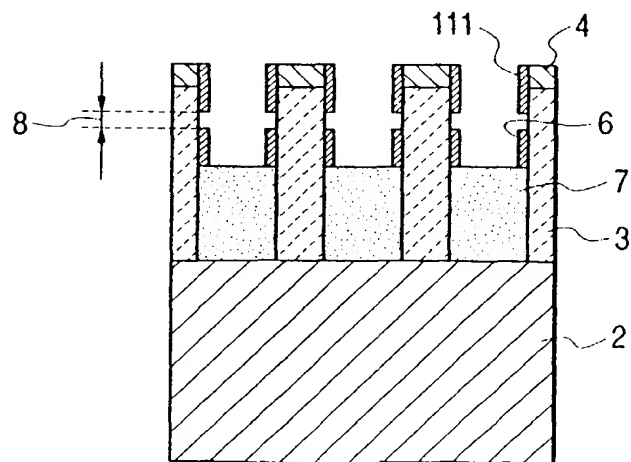


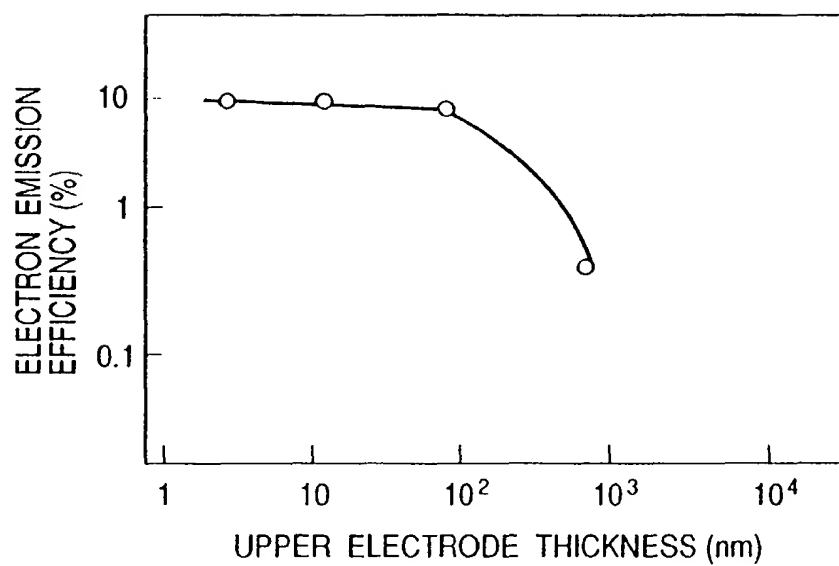
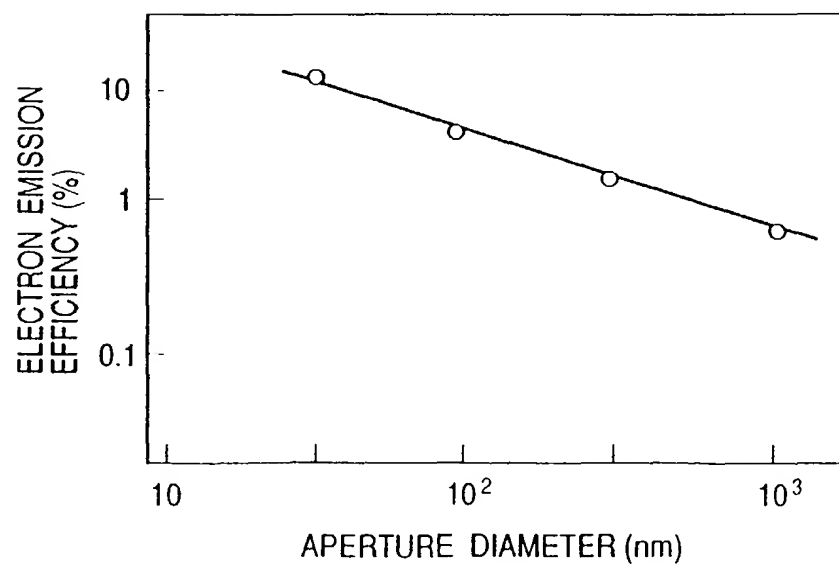
FIG. 18*FIG. 19*

FIG. 20A

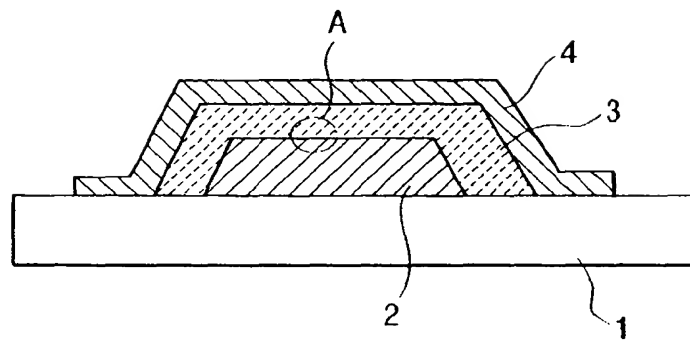


FIG. 20B

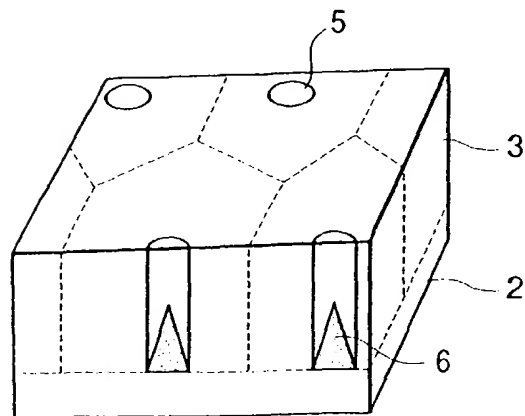


FIG. 21A

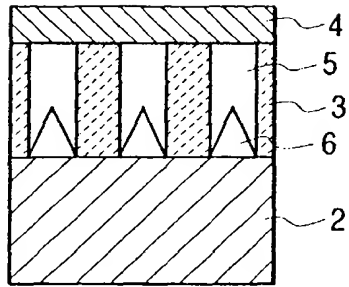


FIG. 21B

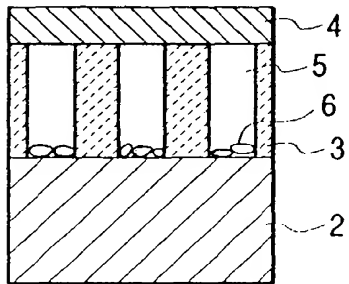


FIG. 21C

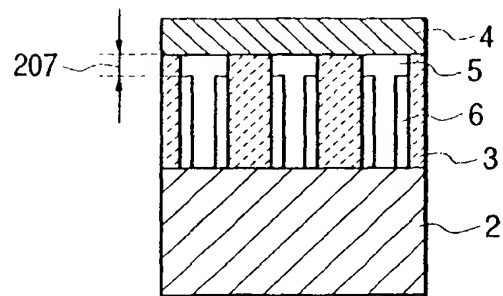


FIG. 21D

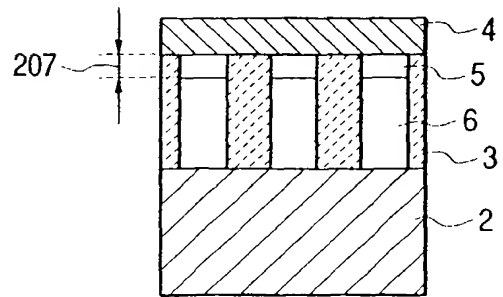


FIG. 22A

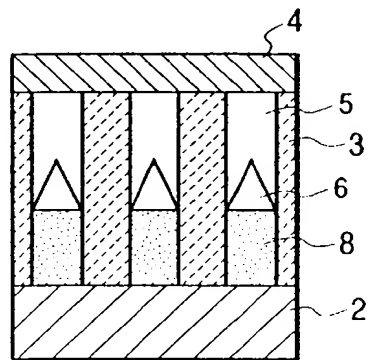


FIG. 22B

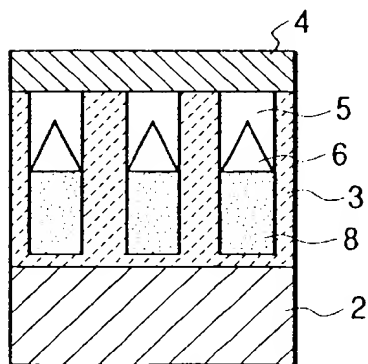


FIG. 23

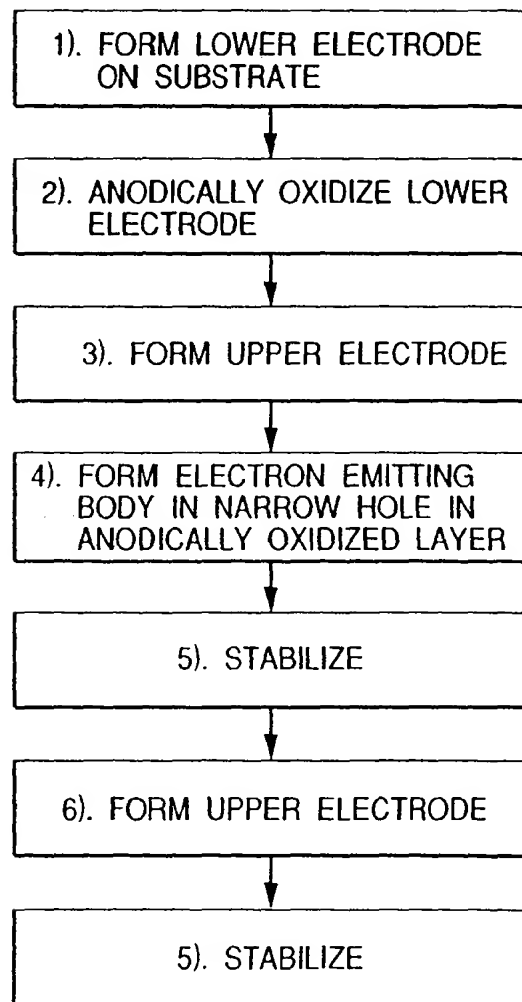


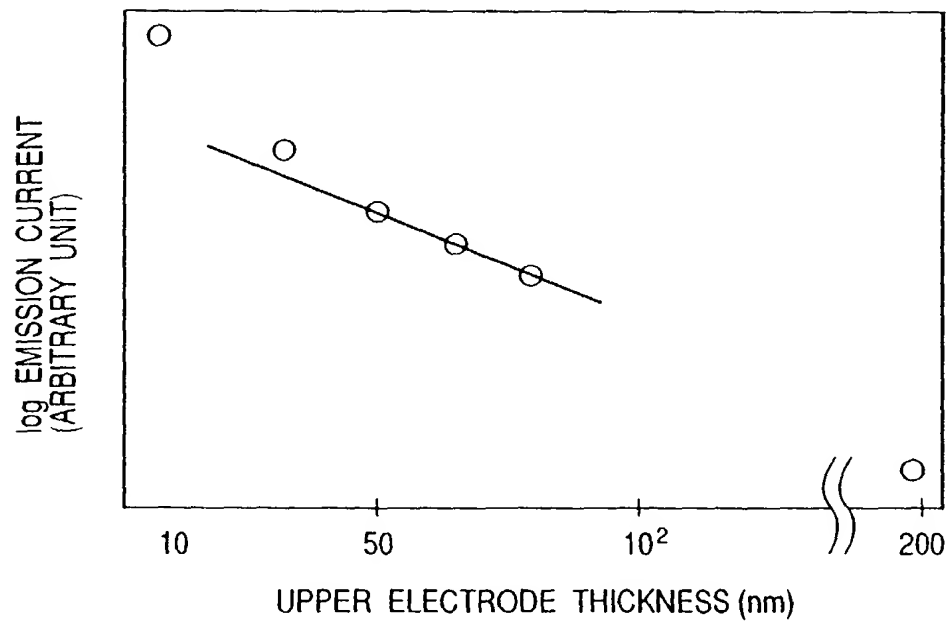
FIG. 24

FIG. 25A

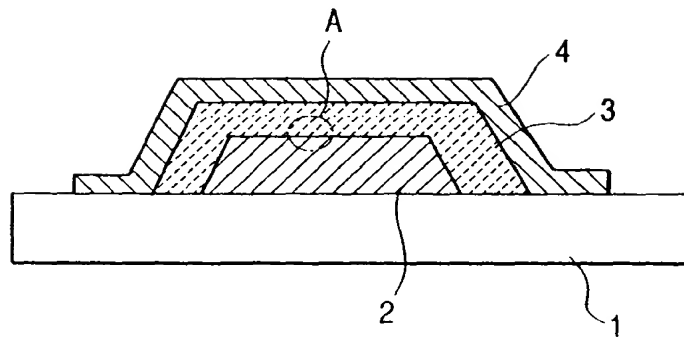


FIG. 25B

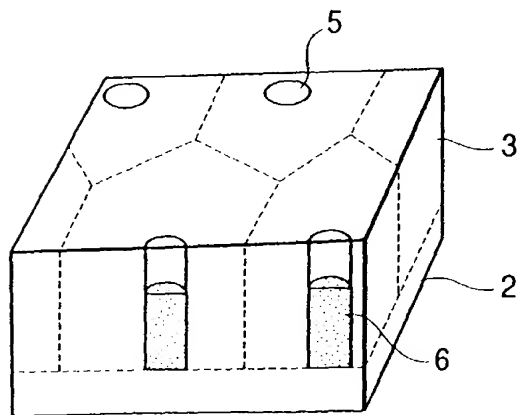


FIG. 26A

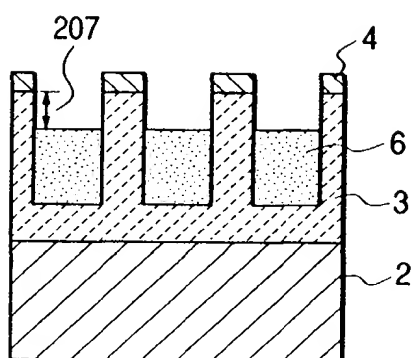


FIG. 26B

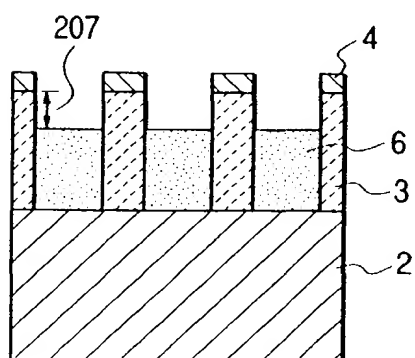


FIG. 27

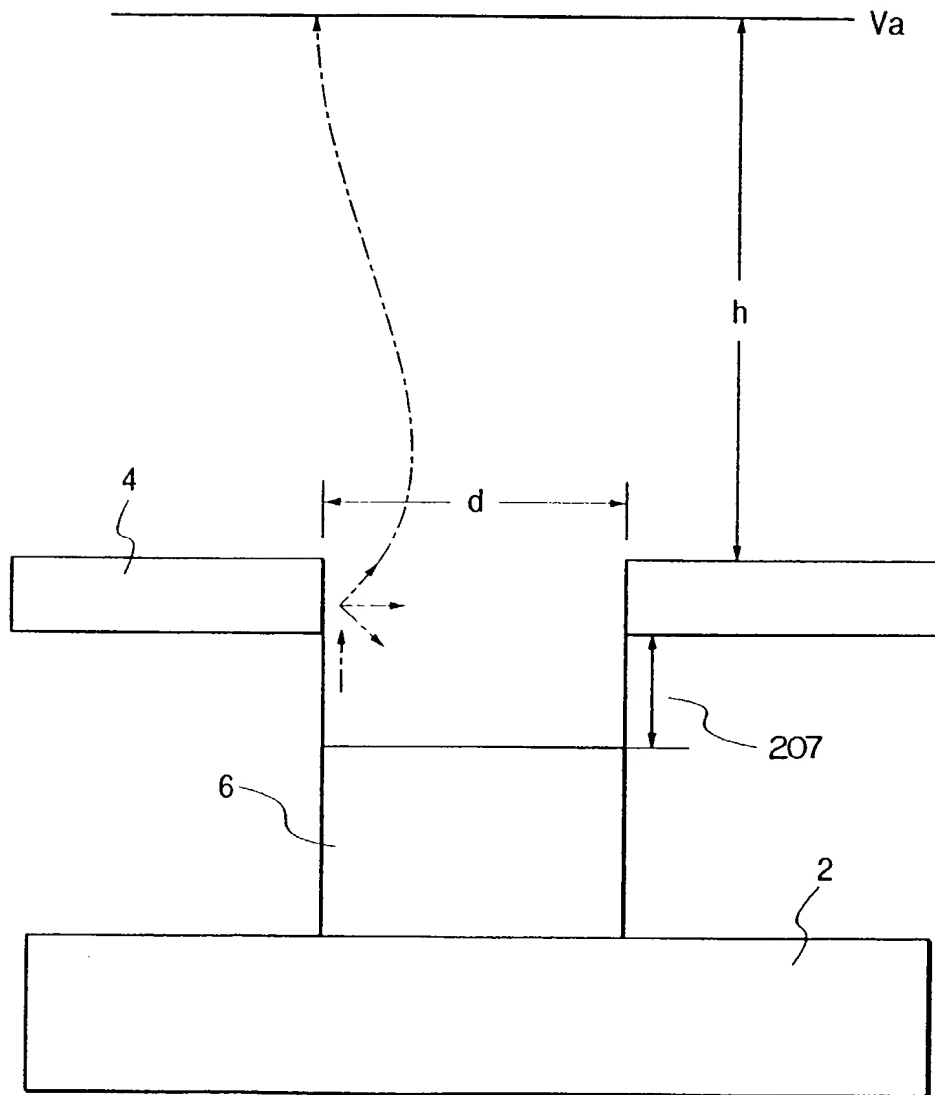


FIG. 28

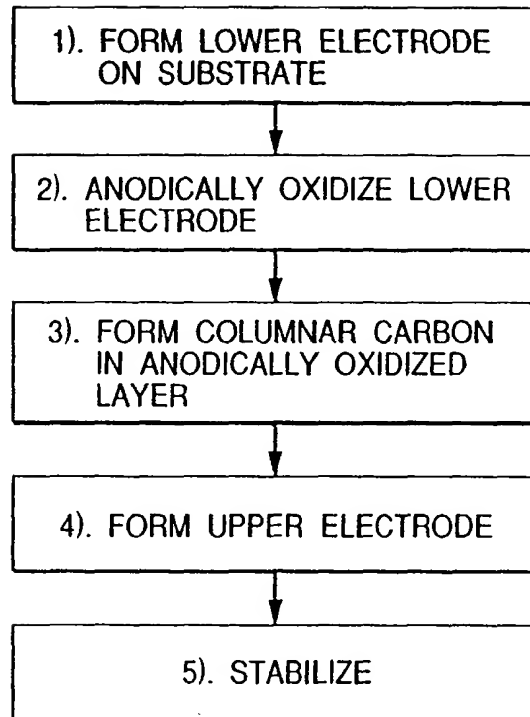


FIG. 29A

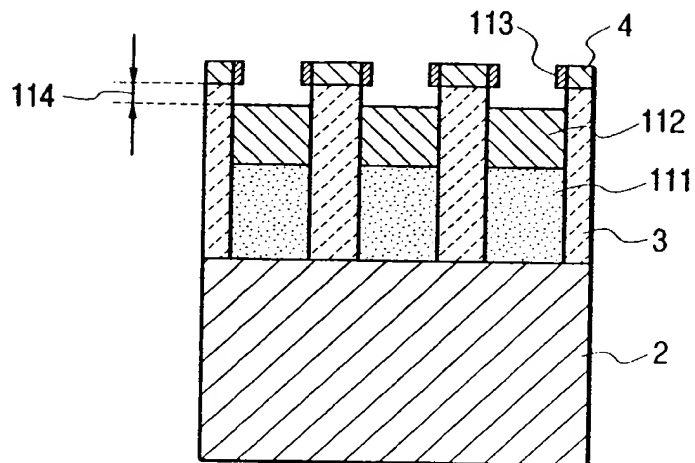


FIG. 29B

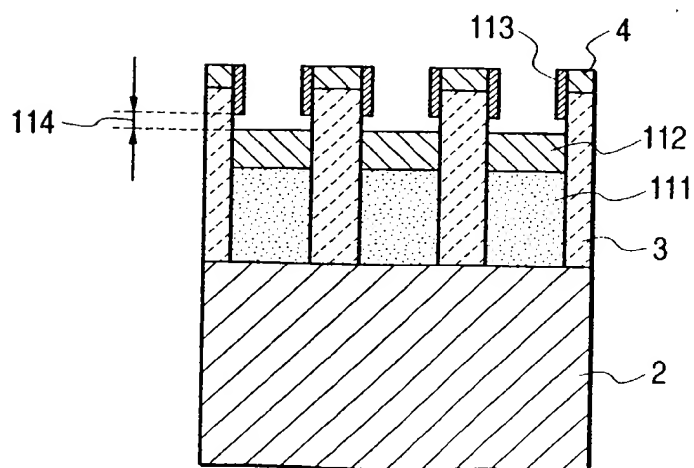


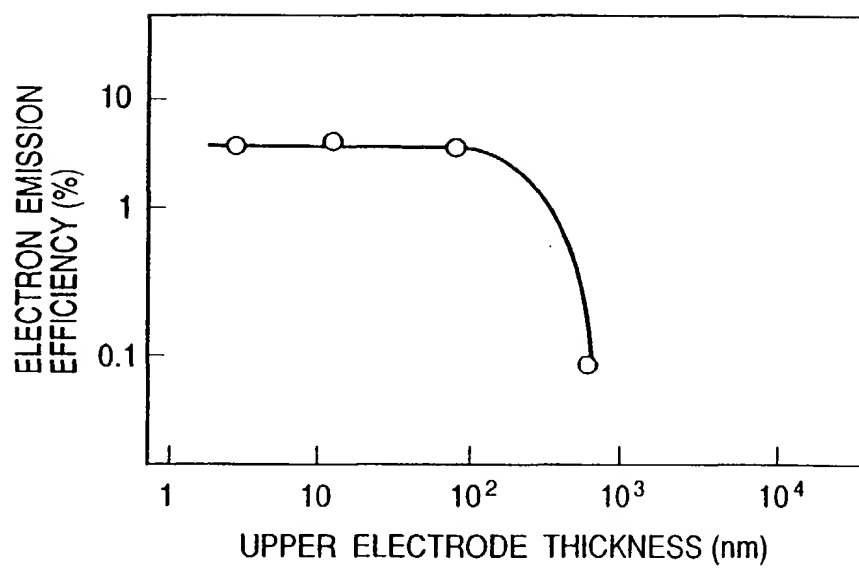
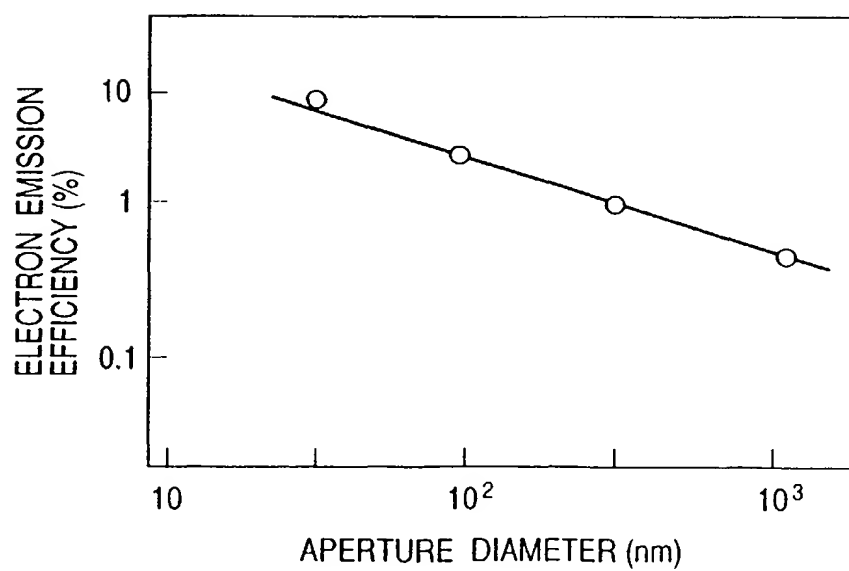
FIG. 30*FIG. 31*

FIG. 32

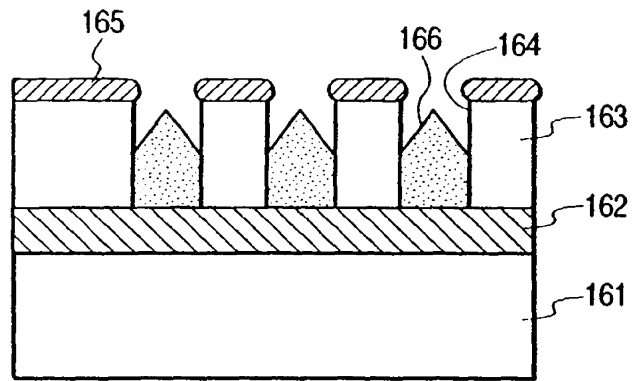


FIG. 33

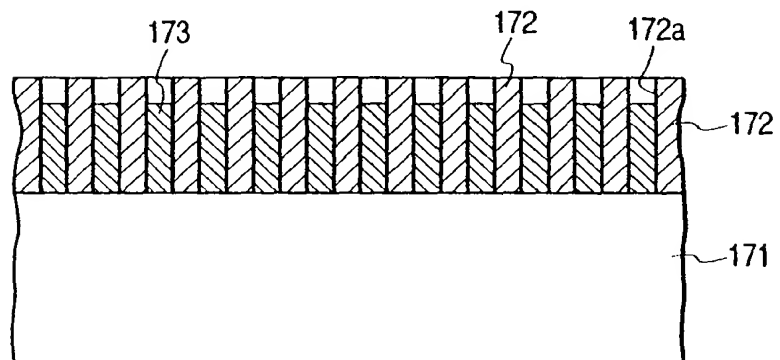


FIG. 34

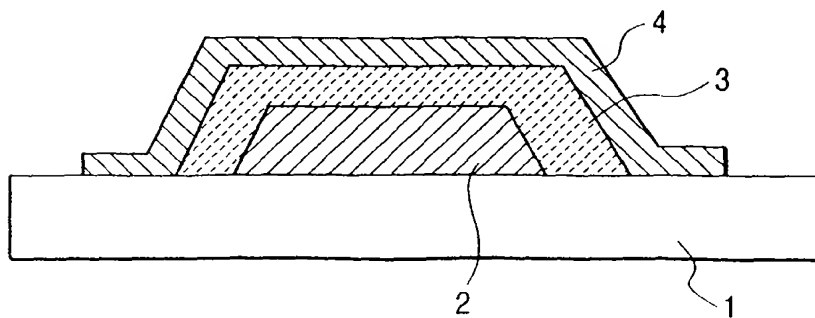
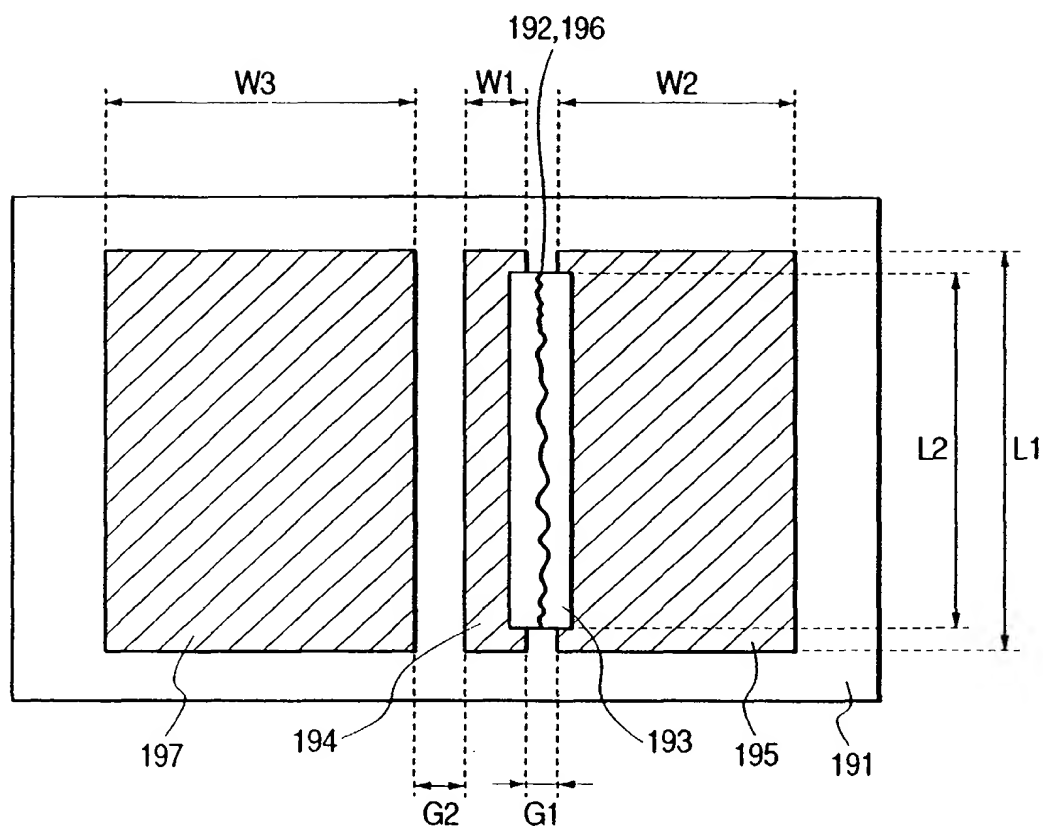
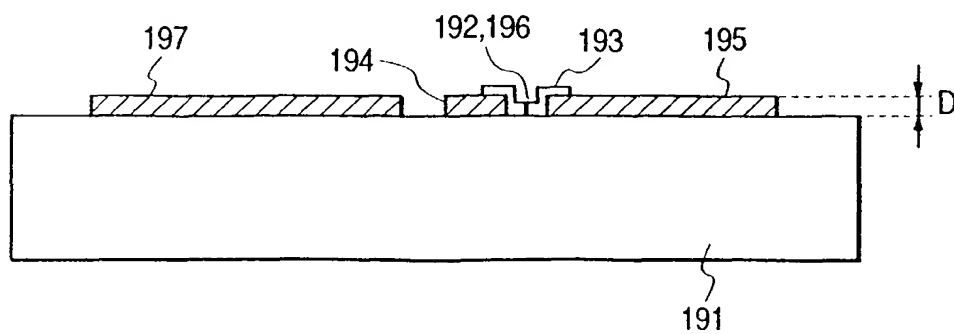


FIG. 35A*FIG. 35B*



- 1 -

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CAU 2817

ELECTRON-EMITTING DEVICE, ELECTRON-EMITTING APPARATUS,
IMAGE DISPLAY APPARATUS, AND LIGHT-EMITTING APPARATUS

BACKGROUND OF THE INVENTION

5 Field of the Invention

The present invention relates to an electron-emitting device, an electron-emitting apparatus, an electron source and an image-forming apparatus. The present invention also relates to a display apparatus such as a television broadcast display, a display for use in a video conference system or a computer display, and to an image-forming apparatus designed as an optical printer using a photosensitive drum or the like.

15 Related Background Art

A field emission (FE) type of electron-emitting device which emits electrons from a surface of a metal when a strong electric field of 10^6 V/cm or higher is applied to the metal, and which is one of the known cold cathode electron sources, is attracting attention.

If the FE-type cold electron source is put to practical use, a thin emissive type image display apparatus can be realized. The FE-type cold electron source also contributes to reductions in power consumption and weight of an image display apparatus.

Fig. 13 shows a vertical FE-type cold electron source structure formed of a substrate 131, an emitter

electrode 132, an insulating layer 133, an emitter 135, and an anode 136. The shape of an electron beam with which the anode is irradiated is indicated by 137.

This structure is of a Spindt type such that an opening
5 is formed in the insulating layer 133 and the gate electrode 134 provided on the cathode 132, and the emitter 135 having a conical shape is placed in the opening. (This type of structure is disclosed by, for example, C.A. Spindt, "Physical Properties of thin-film
10 field emission cathodes with molybdenum cones", J. Appl. Phys., 47, 5248 (1976).)

Fig. 14 shows a lateral FE structure formed of a substrate 141, an emitter electrode 142, an insulating layer 143, an emitter 145, and an anode 146. The shape
15 of an electron beam with which the anode is irradiated is indicated by 147. The emitter 145 having an acute extreme end and the gate electrode 144 for drawing out electrons from the extreme end of the emitter are disposed above and parallel to the substrate, and the
20 collector (anode) is formed above the gate electrode and the emitter electrode remote from the substrate (see USP 4,728,851, USP 4,904,895, etc.).

Also, Japanese Patent Application Laid-open No. 8-115652 discloses an electron-emitting device using
25 fibrous carbon which is deposited in a narrow gap by performing thermal cracking of an organic chemical compound gas on a catalyst metal.

In an image display apparatus using one of the above-described FE-type electron sources, an electron beam spot is obtained which has a size (hereinafter referred to as "beam diameter") depending on the distance H between the electron source and the phosphor, the anode voltage V_a , and the device drive voltage V_f . The beam diameter is smaller than a millimeter and the image display apparatus has sufficiently high resolution.

10 In recent years, however, there has been a tendency to require higher resolution of image display apparatuses.

Further, with the increase in the number of display pixels, power consumption during driving due to the device capacitance of electron-emitting devices is increased. Therefore there is a need to reduce the device capacitance and the drive voltage and to improve the efficiency of electron-emitting devices.

20 In the above-described Spindt type of electron source, the gate is laminated on the substrate with the insulating layer interposed therebetween, so that parasitic capacitances are produced between large capacitances and a multiplicity of emitters. Moreover, the drive voltage is high, several ten to several hundred volts, and capacitive power consumption is disadvantageously large because of the specific structure.

Also, since the beam of electrons drawn out spreads out, there is a need for a focusing electrode for limiting spreading of the beam. For example, Japanese Patent Application Laid-open No. 7-6714
5 discloses a method of converging electron trajectories by disposing an electrode for focusing electrons. This method, however, has the problem of an increase in complexity of the manufacturing process, a reduction in electron emission efficiency, etc., due to the addition
10 of the focusing electrode.

In ordinary lateral FE electron sources, electrons emitted from the cathode are liable to impinge on the opposed gate electrode. Therefore the structure of lateral FE electron sources has the problem of a
15 reduction in the efficiency (the ratio of the electron current flowing through the gate and the electron current reaching the anode) and considerable spreading of the beam shape on the anode.

20 SUMMARY OF THE INVENTION

In view of the above-described problems, an object of the present invention is to provide an electron-emitting device in which the specific capacitance is reduced, which has a lower drive voltage, and which is
25 capable of obtaining a finer electron beam by controlling the trajectory of emitted electrons.

To achieve the above-described object, according

to one aspect of the present invention, there is provided an electron-emitting apparatus comprising:

a first electrode and a second electrode disposed on a surface of a substrate;

5 first voltage application means for applying to the second electrode a potential higher than a potential applied to the first electrode;

an electron-emitting member disposed on the first electrode;

10 a third electrode disposed so as to face the substrate, electrons emitted from the electron-emitting member reaching the third electrode; and

second voltage application means for applying to the third electrode a potential higher than each of the
15 potentials applied to the first and second electrodes, wherein a surface of the electron-emitting member is placed between a plane containing a surface of the second electrode and substantially parallel to the surface of the substrate and a plane containing a
20 surface of the third electrode and substantially parallel to the surface of the substrate. When the distance between the second electrode and the first electrode is d ; the potential difference applied between the second electrode and the first electrode by
25 the first voltage application means is V_1 ; the distance between the third electrode and the substrate is H ; and the potential difference between the potential applied

to the third electrode by the second voltage application means and the potential applied to the first electrode by the first voltage application means is V_2 , then an electric field $E_1 = V_1/d$ is within the
5 range from 1 to 50 times an electric field $E_2 = V_2/H$.

According to another aspect of the present invention, there is provided an electron-emitting apparatus comprising:

a first electrode and a second electrode disposed
10 on a surface of a substrate;

first voltage application means for applying to the second electrode a potential higher than a potential applied to the first electrode;

a plurality of fibers disposed on the first
15 electrode, the fibers containing carbon as a main ingredient;

a third electrode disposed so as to face the substrate, electrons emitted from the fibers reaching the third electrode; and

20 second voltage application means for applying to the third electrode a potential higher than each of the potentials applied to the first and second electrodes, wherein a surface region of the fibers is placed between a plane containing a surface of the second
25 electrode and substantially parallel to the surface of the substrate and a plane containing a surface of the third electrode and substantially parallel to the

surface of the substrate.

In the above-described arrangement, the place at which the electric field concentrates is limited to one side of the region where an emitter material is formed, thereby enabling emitted electrons to be first drawn out toward the extraction electrode (gate electrode) and then made to reach the anode with substantially no possibility of impinging on the extraction electrode. As a result, the electron emission efficiency is improved. Also, there is substantially no possibility of scattering of electrons on the extraction electrode, so that the size of the beam spot obtained on the anode is smaller than that in the conventional device having the problem of scattering on the extraction electrode.

According to still another aspect of the present invention, there is provided an electron-emitting device comprising:

- a fiber containing carbon as a main ingredient;
- and
- an electrode for controlling emission of electrons from the fiber containing carbon as a main ingredient, wherein the fiber containing carbon as a main ingredient has a plurality of layered (laminated) graphenes so as not to be parallel to the axis direction of the fiber.

According to a further aspect of the present invention, there is provided an electron-emitting

device comprising:

a first electrode and a second electrode disposed on a surface of a substrate, a gap being formed between the first and second electrodes; and

5 a fiber provided on the first electrode, the fiber containing carbon as a main ingredient, wherein the second electrode comprises an electrode for controlling emission of electrons from the fiber containing carbon as a main ingredient, and wherein the fiber containing
10 carbon as a main ingredient comprises graphene.

The electron-emitting device of the present invention can stably emit electrons in a low vacuum degree at an increased rate for a long time period.

According to the present invention, a light-
15 emitting member is provided on the anode in the electron-emitting apparatus or above the electron-emitting device to form a light-emitting device, an image display apparatus or the like capable of operating in a low vacuum degree and effecting high-
20 luminance emission/display for a long time period with stability.

BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1A and 1B are diagrams showing an example of
25 a basic electron-emitting device in accordance with the present invention;

Figs. 2A and 2B are diagrams showing a second

embodiment of the present invention;

Figs. 3A and 3B are diagrams showing a third embodiment of the present invention;

Figs. 4A and 4B are diagrams showing a fourth
5 embodiment of the present invention;

Figs. 5A, 5B, 5C, and 5D are diagrams showing fabrication steps in a first embodiment of the present invention;

Fig. 6 is a diagram showing an arrangement for
10 operating the electron-emitting device of the present invention;

Fig. 7 is a diagram showing an operating characteristic of the basic electron-emitting device of the present invention;

15 Fig. 8 is a diagram showing an example of the configuration of a passive matrix circuit using a plurality of electron sources in accordance with the present invention;

Fig. 9 is a diagram showing an example of the
20 construction of an image forming panel using the electron source of the present invention;

Fig. 10 is a diagram showing an example of a circuit for the image forming panel using the electron source of the present invention;

25 Fig. 11 is a diagram schematically showing the structure of a carbon nanotube;

Fig. 12 is a diagram schematically showing the

structure of a graphite nanofiber;

Fig. 13 is a diagram showing a conventional vertical FE structure; and

Fig. 14 is a diagram showing an example of a
5 conventional lateral FE structure.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Preferred embodiments of the present invention will be described in detail with reference to the
10 accompanying drawings. The description of components of the embodiments made below with respect to the size, material and shape of the components and the relative positions of the components is not intended to limit the scope of the present invention except for
15 particular mention of specified details.

The operating voltage V_f of FE devices is generally determined by the electric field at an extreme end of an emitter obtained from the Poisson equation and by the current density of electron
20 emission current according to the relational expression called "Fowler-Nordheim equation" with a work function of the electric field and the emitter portion used as a parameter.

A stronger electric field is obtained as the
25 electric field necessary for emission of electrons as the distance D between the emitter extreme end and the gate electrode is smaller or the radius r of the

emitter extreme end is smaller.

On the other hand, the maximum size X_d in the X-direction of the electron beam obtained on the anode (e.g., the maximum reach from the center of the
5 circular beam shape 137 shown in Fig. 13) is expressed in such a form as to be proportional to (V_f/V_a) in simple calculation.

As is apparent from this relationship, an increase in V_f results in an increase in beam diameter.

10 Consequently, there is a need to minimize the distance D and the radius of curvature r in order to reduce V_f .

Beam shapes in conventional arrangements will be described with reference to Figs. 13 and 14. In Figs.
15 13 and 14, substrates which are corresponding components of the two arrangements are indicated by 131 and 141; emitter electrodes by 132 and 142; insulating layers by 133 and 143; emitters by 135 and 145; anodes by 136 and 146; the shapes of electron beams with which
20 the anodes are irradiated by 137 and 147.

In the case of the Spindt type described above with reference to Fig. 13, when V_f is applied between the emitter 135 and the gate 134, the strength of the electric field at the extreme end of the projection of
25 the emitter, 135 is increased and electrons are thereby taken out of a conical emitter portion about the extreme end into the vacuum.

The electric field at the extreme end of the emitter is formed based on the shape of the extreme end of the emitter to have a certain finite area on the same, so that electrons are perpendicularly drawn out
5 from the finite emitter extreme end area according to the potential.

Simultaneously, other electrons are emitted at various angles. Electrons emitted at larger angles are necessarily drawn toward the gate.

10 As a result, if the gate is formed so as to have a circular opening, the distribution of electrons on the anode 136 shown in Fig. 13 forms a substantially circular beam shape 137. That is, the shape of the beam obtained is closely related to the shape of the
15 drawing gate and to the distance between the gate and the emitter.

In the case of the lateral FE electron source (Fig. 14) in which electrons are drawn out generally along one direction, an extremely strong electric field
20 substantially parallel to the surface of the substrate 141 (lateral electric field) is produced between the emitter 145 and the gate 144, so that part 149 of electrons emitted from the emitter 145 are drawn into the vacuum above the gate 144 while the other electrons
25 are taken into the gate electrode 144.

In the arrangement shown in Fig. 14, electric field vectors toward the anode 146 differ in direction

from those causing emission of electrons (the electric field from the emitter 145 toward the gate 144).

Therefore the distribution of electrons (beam spot) formed by emitted electrons on the anode 146 is

5 increased.

The electric field of electrons drawn out from the emitter electrode 145 (referred to as "lateral electric field" in the following description for convenience sake while the electric field strengthening effect of
10 the emitter configuration is ignored) and the electric field toward the anode (referred to as "vertical electric field" in the following description) will further be described.

The "lateral electric field" can also be expressed
15 as "electric field in a direction substantially parallel to the surface of substrate 131 (141)" in the arrangement shown in Fig. 13 or 14. It can also be expressed as "electric field in the direction of opposition of gate 144 and emitter 145" with respect to
20 the arrangement shown in Fig. 14 in particular.

Also, the "vertical electric field" can also be expressed as "electric field in a direction substantially perpendicular to the surface of substrate 131 (141)" in the arrangement shown in Fig. 13 or 14,
25 or as "electric field in the direction in which the substrate 131 (141) is opposed to the anode 136 (146)".

In the arrangement shown in Fig. 14, as described

above, electrons emitted from the emitter are first drawn out by the lateral electric field, fly toward the gate, and are then moved upward by the vertical electric field to reach the anode.

5 Important factors of this effect are the ratio of the strengths of the lateral and vertical electric fields and the relative position of the electron emission point.

10 When the lateral electric field is stronger than the vertical electric field by an order of magnitude, the trajectories of almost all of electrons drawn out from the emitter are gradually bent by radial potential produced by the lateral electric field so that the electrons fly toward the gate. A part of the electrons
15 impinging on the gate ejects again in a scattering manner. After ejection, however, the electrons repeat scattering while spreading out along the gate by forming elliptical trajectories again and again and while being reduced in number when ejecting until they
20 are caught by the vertical electric field. Only after the scattered electrons have exceeded an equipotential line formed by the gate potential (which line may be called "stagnation point"), they are moved upward by the vertical electric field.

25 When the lateral electric field and the vertical electric field are approximately equal in strength, the restraint imposed by the lateral electric field on

electrons drawn out is reduced, although the trajectories of the electrons are bent by the radial potential. In this case, therefore, electron trajectories appear along which electrons travel to be
5 caught by the vertical electric field without impinging on the gate.

It has been found that if the electron emission position at which electrons are emitted from the emitter is shifted from the gate plane toward the anode
10 plane (see Fig. 6), emitted electrons can form trajectories such as to be caught by the vertical electric field with substantially no possibility of impinging on the gate when the lateral electric field and the vertical electric field are approximately equal
15 in strength, that is, the ratio of the strength of the lateral electric field to that of the vertical electric field is approximately 1 to 1.

Also, a study made of the electric field ratio has shown that if the distance between the gate electrode
20 144 and the extreme end of the emitter electrode 145 is d ; the potential difference (between the gate electrode and the emitter electrode) when the device is driven is V_1 ; the distance between the anode and the substrate (element) is H ; and the potential difference between
25 the anode and the cathode (emitter electrode) is V_2 , a trajectory along which electrons drawn out impinge on the gate is formed when the lateral electric field $E_1 =$

V_1/d is 50 times or more stronger than the vertical electric field $E_2 = V_2/H$.

The inventor of the present invention has also found that a height s (defined as the distance between
5 a plane containing a portion of a gate electrode 2 surface and substantially parallel to a substrate 1 surface and a plane containing an electron-emitting member 4 surface and substantially parallel to the substrate 1 surface (see Fig. 6)) can be determined
10 such that substantially no scattering occurs on the gate electrode 2. The height s depends on the ratio of the vertical electric field and the lateral electric field (vertical electric field strength/lateral electric field strength). As the vertical-lateral
15 electric field ratio is lower, the height s is lower. AS the lateral electric field is stronger, the necessary height s is higher.

The height set in a practical manufacturing process ranges from 10 nm to 10 μm .

20 In the conventional arrangement shown in Fig. 14, the gate 144 and the emitter (142, 145) are formed flush with each other along a common plane and the lateral electric field is stronger than the vertical electric field by an order of magnitude, so that there
25 is a considerable tendency to reduce, by impingement on the gate, the amount of electrons drawn out into the vacuum.

Further, in the conventional arrangement, the structure of the device is determined so as to increase the strength of the electric field in the lateral direction, so that the electron distribution on the anode 146 spreads widely.

As described above, to restrict the distribution of electrons reaching the anode 146, it is necessary (1) to reduce the drive voltage (V_f), (2) to unidirectionally draw out electrons, (3) to consider the trajectory of electrons and, if scattering on the gate occurs, (4) to consider the electron scattering mechanism (elastic scattering in particular).

Therefore the present invention aims to provide an electron-emitting device in which the distribution of electrons with which the anode surface is irradiated is made finer, and in which the electron emission efficiency is improved (the amount of emitted electrons absorbed in the gate electrode is reduced).

The structure of a novel electron-emitting device in accordance with the present invention will now be described below in detail.

Fig. 1A is a schematic plan view showing an example of an electron-emitting device in accordance with the present invention. Fig. 1B is a cross-sectional view taken along the line 1B-1B of Fig. 1A. Fig. 6 is schematic cross-sectional view of the electron-emitting apparatus of the present invention in

a state where the electron-emitting apparatus having an anode disposed above the electron-emitting device of the present invention is being driven.

In Figs. 1A, 1B and 6 are illustrated an
5 insulating substrate 1, an extraction electrode 2 (also referred to as "gate electrode" or "second electrode"), a cathode 3 (also referred to as "first electrode"), an electron-emitting material 4 provided on the cathode 3 (also referred to as "electron-emitting member" or
10 "emitter material"), and an anode 61 (also referred to as "third electrode").

In the electron-emitting apparatus of the present invention, if as shown in Figs. 1A, 1B and 6 the distance by which the cathode 3 and the gate electrode
15 2 are spaced apart from each other is d ; the potential difference (the voltage between the cathode 3 and the gate electrode 2) when the electron-emitting device is driven is V_f ; the distance between the anode 61 and the surface of the substrate 1 on which the electron-
20 emitting device is arranged is H ; and the potential difference between the anode 61 and the cathode 3 is V_a , an electric field produced to drive the device (lateral electric field): $E_1 = V_f/d$ is set within the range from 1 to 50 times an electric field between the
25 anode and the cathode (vertical electric field): $E_2 = V_a/H$.

The proportion of electrons impinging on the gate

electrode 2 in electrons emitted from the cathode 3 is reduced thereby. In this manner, a high-efficiency electron-emitting device capable of preventing an emitted electron beam from spreading out widely can be
5 obtained.

The "lateral electric field" referred to in the description of the present invention can also be expressed as "electric field in a direction substantially parallel to the surface of substrate 1".
10 It can also be expressed as "electric field in the direction in which the gate 2 is opposed to the cathode 3".

Also, the "vertical electric field" referred to in the description of the present invention can also be
15 expressed as "electric field in a direction substantially perpendicular to the surface of substrate 1". It can also be expressed as "electric field in the direction in which the substrate 1 is opposed to the anode 61".

20 Further, in the electron-emitting apparatus of the present invention, a plane containing the surface of the electron-emitting member 4 and substantially parallel to the surface of the substrate 1 is spaced apart from a plane containing a portion of the surface
25 of the gate electrode 2 and substantially parallel to the surface of the substrate 1 (see Fig. 6). In other words, in the electron-emitting apparatus of the

present invention, a plane containing the surface of the electron-emitting member 4 and substantially parallel to the surface of the substrate 1 is placed between the anode 61 and a plane containing a portion of the surface of the gate electrode 2 and substantially parallel to the substrate surface (see Fig. 6).

Further, in the electron-emitting device of the present invention, the electron-emitting member 4 is placed at a height s (defined as the distance between the plane containing a portion of the surface of gate electrode 2 and substantially parallel to the surface of substrate 1 and the plane containing the surface of electron-emitting member 4 and substantially parallel to the surface of substrate 1 (see Fig. 6)) such that substantially no scattering occurs on the gate electrode 2.

The height s depends on the ratio of the vertical electric field and the lateral electric field (vertical electric field strength/lateral electric field strength). As the vertical-lateral electric field ratio is lower, the height s is lower. As the lateral electric field is stronger, the necessary height s is higher. Practically, the height is not less than 10 nm not more than 10 μm .

Examples of the insulating substrate 1 are the following substrates whose surfaces are sufficiently cleansed: quartz glass; glass in which the content of

an impurity such as Na is reduced by partial substitution by K, for example; a laminate formed in such a manner that SiO_2 is laminated by sputtering or the like on soda lime glass, a silicon substrate or the like; and an insulating substrate made of a ceramic such as alumina.

Each of the extraction electrode 2 and cathode 3 is an electrically conductive member formed on the surface of the substrate 1 by an ordinary vacuum film forming technique, such as evaporation or sputtering, or a photolithography technique so as to face each other. The material of the electrodes 2 and 3 is selected from, for example, carbon, metals, nitrides of metals, carbides of metals, borides of metals, semiconductors, and metallic compounds of semiconductors. The thickness of the electrodes 2 and 3 is set within the range from several ten nanometers to several ten microns. Preferably, the material of the electrodes 2 and 3 is a heat resistant material formed of carbon, a metal, a nitride of a metal or a carbide of a metal.

The material of the electrodes 2 and 3 constituting the electron-emitting device in accordance with the present invention are disposed on the surface of the substrate 1. Needless to say, the extraction electrode 2 and the cathode 3 are spaced apart from each other along a direction substantially parallel to

the plane containing the surface of the substrate 1.
In other words, the electron-emitting device is
constructed so that the extraction electrode 2 and the
cathode 3 do not overlap each other.

5 In particular, in the case of growth of fibrous
carbon described below, the electrodes are preferably
formed of silicon having conductivity, e.g., doped
polysilicon or the like.

 If there is apprehension about, for example, a
10 voltage drop due to the small thickness of the
electrodes, or if a plurality of the electron-emitting
devices are used in matrix form, a low-resistance
wiring metallic material may be used to form suitable
wiring portions on condition that it does not affect
15 emission of electrons.

 The emitter material (electron-emitting member) 4
may be formed in such a manner that a film deposited by
an ordinary vacuum film forming method such as
sputtering is worked into the shape of the emitter by
20 using a technique such as reactive ion etching (RIE).
Alternatively, it may be formed by growing needle
crystals or whiskers by seed growth in chemical vapor
deposition (CVD). In the case of RIE, the control of
the emitter shape depends on the kind of the substrate
25 used, the kind of gas, the gas pressure (flow rate),
the etching time, the energy for forming plasma, etc.
In a CVD forming process, the emitter shape is

controlled by selecting the kind of the substrate, the kind of gas, the flow rate, the growth temperature, etc.

Examples of the material used to form the emitter (electron-emitting member) 4 are carbides, such as TiC, ZrC, HfC, TaC, SiC, and WC, amorphous carbon, graphite, diamondlike carbon, carbon containing dispersed diamond, and carbon compounds.

According to the present invention, fibrous carbon is particularly preferably used as the material of the emitter (electron-emitting member) 4. "Fibrous carbon" referred to in the description of the present invention can also be expressed as "material in columnar form containing carbon as a main constituent" or "material in filament form containing carbon as a main constituent". Further, "fibrous carbon" can also be expressed as "fibers containing carbon as a main constituent". More specifically, "fibrous carbon" in accordance with the present invention comprises carbon nanotubes, graphite nanofibers, and amorphous carbon fibers. In particular, graphite nanofibers are most preferred as electron-emitting member 4.

The gap between the extraction electrode 2 and the cathode 3 and the drive voltage (the voltage applied between the extraction electrode 2 and the cathode 3) may be determined so that the value of the lateral electric field necessary for emission of electrons from

the cathode material used is 1 to 50 times larger than that of the vertical electric field necessary for forming an image, as described above.

In a case where a light-emitting member such as a phosphor is provided on the anode, the necessary vertical electric field is, preferably, within the 10^{-1} to 10 V/ μm range. For example, in a case where the gap between the anode and the cathode is 2 mm and 10 kV is applied between the anode and the cathode, the vertical electric field is 5 V/ μm . In this case, the emitter material (electron-emitting member) 4 to be used has an electron-emitting electric field value of 5 V/ μm or higher. The gap and the drive voltage may be determined in correspondence with the selected electron-emitting electric field value.

An example of a material having an electric field threshold of several V/ μm is fibrous carbon. Each of Figs. 11 and 12 shows an example of the configuration of fibrous carbon. In each of Figs. 11 and 12, the configuration is schematically shown at the optical microscope level (to 1,000 times) in the left-hand section, at the scanning electron microscope level (to 30,000 times) in the middle section, and at the transmission electron microscope level (to 1,000,000 times) in the right-hand section.

A graphene structure formed into a cylinder such as that shown in Fig. 11 is called a carbon nanotube (a

multilayer cylindrical graphene structure is called a multiwall nanotube). Its threshold value is minimized when the tube end is opened.

The fibrous carbon shown in Fig. 12 may be
5 produced at a comparatively low temperature. Fibrous carbon having such a configuration is composed of a graphene layered body (thus, it may be referred to as "graphite nanofiber", and has an amorphous structure whose ratio is increased with temperature). More
10 specifically, "graphite nanofiber" designates a fibrous substance in which graphenes are layered (laminated) in the longitudinal direction thereof (in the axis direction of the fiber). In other words, graphite nanofiber is a fibrous substance in which a plurality
15 of graphenes are arranged and layered (laminated) so as not to be parallel to the fiber axis, as shown in Fig. 12.

On the other hand, a carbon nanotube is a fibrous substance in which graphenes are arranged (in
20 cylindrical shape) around the longitudinal direction (fiber axis direction). In other words, it is a fibrous substance in which graphenes are arranged substantially parallel to the fiber axis.

One layer of graphite is called "graphene" or
25 "graphene sheet". More specifically, graphite is formed in such a manner that carbon planes on which carbon atoms are arrayed so as to form regular hexagons

close to each other by covalent bond in sp^2 hybridization are laid one on another while being spaced by a distance of 3.354\AA . Each carbon plane is called "graphene" or "graphene sheet".

5 Each type of fibrous carbon has an electron emission threshold value of about 1 to $10\text{ V}/\mu\text{m}$ and is therefore preferred as the material of the emitter (electron-emitting member) 4 in accordance with the present invention.

10 In particular, electron-emitting devices using graphite nanofibers, not limited to the device structure of the present invention shown in Fig. 1, etc., are capable of causing emission of electrons in a low electric field to obtain a large emission current,
15 and can be readily manufactured to obtain as an electron-emitting device having stable electron-emitting characteristics. For example, such an electron-emitting element can be obtained by forming graphite nanofibers as an emitter and by providing an
20 electrode for controlling emission of electrons from the emitter. Further, if a light emitting member capable of emitting light when irradiated with electrons emitted from graphite nanofibers is used, a light emitting device such as a lamp can be formed.
25 Further, an image display apparatus may be constructed by forming an array of a plurality of the above-described electron-emitting devices and by preparing an

anode having a light emitting material such as a phosphor. In the electron-emitting device, the light emitting device or the image display apparatus using above-described graphite nanofibers, stable emission of
5 electrons can be achieved without maintaining inside the device or the apparatus an ultrahigh vacuum such as that required in conventional electron-emitting devices. Moreover, since electrons are emitted by a low electric field, the device or apparatus can be
10 easily manufactured with improved reliability.

The above-described fibrous carbon can be formed by decomposing a hydrocarbon gas by using a catalyst (a material for accelerating deposition of carbon). The processes for forming carbon nanotubes and graphite
15 nanofibers differ in the kind of catalyst and decomposition temperature.

The catalytic material may be a material which is used as a seed for forming fibrous carbon, and which is selected from Fe, Co, Pd, Ni, and alloys of some of
20 these materials.

In particular, if Pd or Ni is used, graphite nanofibers can be formed at a low temperature (not lower than 400°C). The necessary carbon nanotube forming temperature in the case of using Fe or Co is
25 800°C or higher. Also, the process of producing a graphite nanofiber material by using Pd or Ni, which can be performed at a lower temperature, is preferred

from the viewpoint of reducing the influence on other components and limiting the manufacturing cost.

Further, the characteristic of Pd that resides in enabling oxides to be reduced by hydrogen at a low
5 temperature (room temperature) may be utilized. That is, palladium oxide may be used as a seed forming material.

If hydrogen reduction using palladium oxide is performed, an initial agglomeration seed can be formed
10 at a comparatively low temperature (equal to or lower than 200°C) without metallic film thermal agglomeration or ultrafine particle forming/deposition conventionally used as ordinary seed forming techniques.

The above-mentioned hydrocarbon gas may be, for
15 example, acetylene, ethylene, methane, propane, or propylene. Further, CO or CO₂ gas or vapor of an organic solvent such as ethanol or acetone may be used in some case.

In the device of the present invention, the region
20 where the emitter (electron-emitting member) exists will be referred to as "emitter region" regardless of contribution to emission of electrons.

The position of the electron emission point (electron-emitting portion) in the "emitter region" and
25 the electron-emitting operation will be described with reference to Figs. 6 and 7.

The electron-emitting device having the distance

between the cathode 3 and the extraction electrode 2 to several microns was set in a vacuum apparatus 60 such as shown in Fig. 6. A sufficiently high degree of vacuum about 10^{-4} Pa was produced by a evacuating pump 65. A potential (voltage V_a) higher by several kilovolts than that of the cathode 3 and the extraction electrode was applied from a voltage source ("second voltage application means" or "second potential application means") to the anode 61, which was placed so that the surface of the anode 61 is at the height H , which was several millimeters, from the surface of the substrate 1, as shown in Fig. 6. While the voltage V_a was applied between the cathode 3 and the anode 61, the voltage applied to the anode may be a voltage from the ground potential. The substrate 1 and the anode 61 were positioned relative to each other so that their surfaces are parallel to each other.

Between the cathode 3 and the extraction electrode 2 of the electron-emitting device, a voltage of about several ten volts was applied as drive voltage V_f from a power supply (not shown) ("first voltage application means" or "first potential application means"). Device current I_f flowing between the electrodes 2 and 3 and electron emission current I_e flowing through the anode were measured.

It is supposed that, during this operation, equipotential lines 63 are formed as shown in Fig. 6

(an electric field (the direction of an electric field) substantially parallel to the surface of the substrate 1, and that the concentration of the electric field is maximized at the point on a portion of the electron-emitting member 4 closest to the anode and facing the gap, as indicated by 64. It is thought that electrons are emitted mainly from the portion of the electron-emitting material in the vicinity of this electric field concentration point, where the concentration of the electric field is maximized. An I_e characteristic such as shown in Fig. 7 was obtained. That is, I_e rises abruptly at a voltage about half the applied voltage. The I_f characteristic (not shown) was similar to the I_e characteristic but the value of I_f was sufficiently smaller than that of I_e .

An electron source obtained by arranging a plurality of the electron-emitting devices in accordance with the present invention will be described with reference to Fig. 8. In Fig. 8 are illustrated an electron source substrate 81, X-direction wiring 82, Y-direction wiring 83, electron-emitting device 84 in accordance with the present invention, and a connecting conductor 85.

X-direction wiring 82 has m conductors $DX1, DX2, \dots, DXm$, which may be constituted by, for example, a conductive metal formed by vacuum evaporation, printing, sputtering, or the like. The material, film

thickness, and width of the wiring are selected according to a suitable design. Y-direction wiring 83 has n conductors DY1, DY2, ... DY n and is formed in the same manner as X-direction wiring 82. An interlayer
5 insulating layer (not shown) is provided between the m conductors of X-direction wiring 82 and the n conductors of Y-direction wiring 83 to electrically separate these conductors (each of m and n is a positive integer).

10 The interlayer insulating layer (not shown) is, for example, a SiO₂ layer formed by vacuum evaporation, printing, sputtering, or the like. For example, the interlayer insulating film is formed in the desired shape over the whole or part of the surface of the
15 substrate 81 on which X-direction wiring 82 has been formed and the film thickness, material and fabrication method are selected to ensure withstanding against the potential difference at the intersections of the conductors of X-direction wiring 82 and Y-direction
20 wiring 83 in particular. The conductors of X-direction wiring 82 and Y-direction wiring 83 are respectively extended outward as external terminals.

Pairs of electrodes (not shown) constituting electron-emitting devices 84 are electrically connected
25 to the m conductors of X-direction wiring 82 and the n conductors of Y-direction wiring 83 by connecting conductors 85 made of a conductive metal or the like.

The materials forming wiring 82 and wiring 83, the material forming the connecting conductors 85 and the materials forming the pairs of device electrodes may be entirely constituted of common constituent elements or
5 partially constituted of common constituent elements, or may be constituted of different constituent elements. These materials are selected from, for example, the above-described device electrode materials. If the materials of the device electrodes
10 and the wiring materials are the same, the wiring conductors connected to the device electrodes can be considered to be device electrodes.

A scanning signal application means (not shown) for applying scanning signals for selecting the rows of
15 electron-emitting devices 84 arranged in the X-direction is connected to X-direction wiring 82. On the other hand, a modulation signal generation means for modulating voltages applied to the columns of electron-emitting devices 84 arranged in the Y-
20 direction according to input signals is connected to Y-direction wiring 83. The drive voltage applied to each electron-emitting device is supplied as a voltage corresponding to the difference between the scanning signal and the modulation signal applied to the
25 element.

In the above-described arrangement, each device can be selected by using the passive-matrix wiring to

be driven independently.

An image forming apparatus constructed by using an electron source having such a passive matrix array will be described with reference to Fig. 9. Fig. 9

5 schematically shows an example of the display panel of the image forming apparatus. Referring to Fig. 9, a plurality of electron-emitting devices are disposed on an electron source substrate 81, which is fixed on a rear plate 91. A face plate 96 has a glass substrate
10 93, a phosphor film 94 provided as a light emitting member on the internal surface of the glass substrate 93, a metal back (anode) 95, etc. The rear plate 91 and the face plate 96 are connected to a supporting frame 92 by using frit glass or the like. An envelop
15 97 is formed by being seal-bonded by baking in, for example, atmospheric air, a vacuum or in nitrogen in the 400 to 500°C temperature range for 10 minutes or longer.

The envelop 97, as described above, is constituted
20 by the face plate 96, the supporting frame 92, and the rear plate 91. The rear plate 91 is provided mainly for the purpose of reinforcing the substrate 81. If the substrate 81 itself has sufficiently high strength, there is no need to separately provide the rear plate
25 91. That is, the supporting frame 92 may be directly seal-bonded to the substrate 81 and the envelop 97 may be formed by the frame plate 96, the supporting frame

92 and the substrate 81. A supporting member (not shown) called a spacer may be provided between the face plate 96 and the rear plate 91 to enable the envelop 97 to have a sufficiently high strength for resisting atmospheric pressure.

Embodiments of the present invention will be described below in detail.

(Embodiment 1)

Fig. 1A shows a top view of an electron-emitting device fabricated in this embodiment. Fig. 1B is a cross-sectional view taken along the line 1B-1B of Fig. 1A.

Figs. 1A and 1B illustrate an insulating substrate 1, an extraction electrode 2 (gate), a cathode 3, and an emitter material 4.

The process of fabricating the electron-emitting device of this embodiment will be described in detail. (Step 1)

A quartz substrate was used as substrate 1. After sufficiently cleansing the substrate, a 5 nm thick Ti film (not shown) and a 30 nm thick poly-Si film (arsenic doped) were successively deposited by sputtering on the substrate as gate electrode 2 and cathode 3.

Next, a resist pattern was formed by photolithography using a positive photoresist (AZ1500/ from Clariant Corporation).

Thereafter, dry etching was performed on the poly-Si (arsenic doped) layer and Ti layer with the patterned photoresist used as a mask, CF_4 gas being used to etch the Ti layer. An extraction electrode 2 and a
5 cathode 3 having a gap of 5 μm therebetween were thereby formed (Fig. 5A).

(Step 2)

Next, a Cr having a thickness of about 100 nm was deposited on the entire substrate by electron beam (EB)
10 evaporation.

A resist pattern was formed by photolithography using a positive photoresist (AZ1500/ from Clariant Corporation).

An opening corresponding to a region (100 μm
15 square) where electron-emitting material 4 was to be provided was formed on the cathode 3 with the patterned photoresist used as a mask. Cr at the opening was removed by using a cerium nitrate etching solution.

After removing the resist, a complex solution
20 prepared by adding isopropyl alcohol, etc., to a Pd complex was applied to the entire substrate by spin coating.

After application of the solution, a heat treatment was performed in atmospheric air at 300°C to
25 form a palladium oxide layer 51 having a thickness of about 10 nm. Thereafter, Cr was removed by using a cerium nitrate etching solution (Fig. 5B).

(Step 3)

The substrate was baked at 200°C, atmospheric air was evacuated, and a heat treatment was then performed in 2% hydrogen flow diluted with nitrogen. At this stage, particles 52 having a diameter of about 3 to 10 nm were formed on the surface of the cathode 3. The density of the particles at this stage was estimated at about 10^{11} to 10^{12} particles/cm² (Fig. 5C).

(Step 4)

Subsequently, a heat treatment was performed in a 0.1% ethylene flow diluted with nitrogen at 500°C for 10 minutes. The state after the heat treatment was observed with a scanning electron microscope to find that a multiplicity of fibrous carbon 4 having a diameter of about 10 to 25 nm and extending like fibers while curving or bending had been formed in the Pd-coated region. The thickness of the fibrous carbon layer was about 500 nm (Fig. 5D).

This electron-emitting device was set in the vacuum apparatus 60 shown in Fig. 6. A sufficiently high vacuum of about 2×10^{-5} Pa was produced by the evacuating pump 62. Voltage $V_a = 10$ kV was applied as anode voltage to the anode 61 distanced by $H = 2$ mm from the device, as shown in Fig. 6. Also, a pulse voltage of $V_f = 20$ V was applied as drive voltage to the device. Device current I_f and electron emission current I_e thereby caused were measured.

The I_f and I_e characteristics of the electron-emitting device were as shown in Fig. 7. That is, I_e rises abruptly at a voltage about half the applied voltage, and a current of about 1 μ A was measured as electron emission current I_e at a V_f value of 15 V. On the other hand, the I_f characteristic was similar to the I_e characteristic but the value of I_f was smaller than that of I_e by an order of magnitude or more.

The obtained beam had a generally rectangular shape having a longer side along the Y-direction and a shorter side in the X-direction. The beam width was measured with respect to different gaps of 1 μ m and 5 μ m between the electrodes 2 and 3 while V_f was fixed at 15 V and the distance H to the anode was fixed at 2 mm. Table 1 shows the results of this measurement.

Table 1

	$V_a = 5 \text{ kV}$	$V_a = 10 \text{ kV}$
Gap: 1 μ m	60 μ m in x-direction 170 μ m in y-direction	30 μ m in x-direction 150 μ m in y-direction
Gap: 5 μ m	93 μ m in x-direction 170 μ m in y-direction	72 μ m in x-direction 150 μ m in y-direction

It was possible to change the necessary electric field for driving by changing the fibrous carbon growth conditions. In particular, the average particle size of Pd particles formed by reduction of palladium oxide

is related to the diameter of fibrous carbon thereafter grown. It was possible to control the average Pd particle size through the Pd density in the Pd complex coating and the rotational speed of spin coating.

5 The fibrous carbon of this electron-emitting device was observed with the transmission electron microscope to recognize a structure in which graphenes are layered in the fiber axis direction, as shown in the right-hand section of Fig. 12. The graphene
10 stacking intervals (in the Z-axis direction) resulting from heating at a lower temperature, about 500°C were indefinite and was 0.4 nm. As the heating temperature was increased, the grating intervals became definite. The intervals resulting from heating at 700°C were 0.34
15 nm, which is close to 0.335 nm in graphite.

(Embodiment 2)

Fig. 2 shows a second embodiment of the present invention.

20 In this embodiment, an electron-emitting device was fabricated in the same manner as that in the first embodiment except that the cathode 3 corresponding to that in the first embodiment had a thickness of 500 nm and fibrous carbon provided as electron-emitting
25 material 4 had a thickness of 100 nm. Currents I_f and I_e in the fabricated electron-emitting device were measured.

In this device arrangement, the electron emission

point was positively heightened (toward the anode)
relative to the gate electrode by increasing the
thickness of the cathode 3. Trajectories along which
electrons impinge on the gate were thereby reduced,
5 thereby preventing a reduction in efficiency and
occurrence of a beam-thickening phenomenon.

Also in this device arrangement, the electron
emission current I_e at $V_f = 20V$ was about $1\mu A$. On the
other hand, the I_f characteristic was similar to the I_e
10 characteristic but the value of I_f was smaller than
that of I_e by two orders of magnitude.

The results of measurement of the beam diameter in
this embodiment were substantially the same as those
shown in Table 1.

15 (Embodiment 3)

Fig. 3 shows a third embodiment of the present
invention.

In this embodiment, in the step corresponding to
step 2 in the first embodiment, palladium oxide 51 was
20 provided on the cathode 3 and in the gap between the
electrodes 2 and 3. Pd oxide was provided in the gap
in such a manner as to extend from the cathode 3 to a
point near the midpoint of the gap. Excepting step 2,
this embodiment is the same as the first embodiment.

25 The electric field in the electron-emitting device
of this embodiment was twice as strong as that in the
first embodiment because the gap was reduced, thereby
enabling the drive voltage to be reduced to about 8 V.

(Embodiment 4)

Fig. 4 shows a fourth embodiment of the present invention. In this embodiment step 1 and step 2 described above with respect to the first embodiment
5 are changed as described below.

(Step 1)

A quartz substrate was used as substrate 1. After sufficiently cleansing the substrate, a 5 nm thick Ti film and a 30 nm thick poly-Si film (arsenic doped)
10 were successively deposited by sputtering on the substrate as cathode 3.

Next, a resist pattern was formed by photolithography using a positive photoresist (AZ1500/ from Clariant Corporation).

15 Next, dry etching was performed on the poly-Si layer and Ti layer by using CF_4 gas, with the patterned photoresist used as a mask. Cathode 3 was thereby formed.

The quartz substrate was then etched to a depth of
20 about 500 nm by using a mixed acid formed of hydrofluoric acid and ammonium fluoride.

Subsequently, a 5 nm thick Ti film and a 30 nm thick Pt film were successively deposited on the substrate as gate electrode 2 by again performing
25 sputtering. After removing the photoresist from the cathode, a resist pattern was again formed by using a positive photoresist (AZ1500/ from Clariant

Corporation) to form the gate electrode.

Next, dry etching was performed on the Pt layer and Ti layer by using Ar, with the patterned photoresist used as a mask. Electrode 2 was thereby
5 formed so that the step formed between the electrodes functions as a gap.

Next, a resist pattern was formed on the cathode, a Ni film having a thickness of about 5 nm was formed by resistance heating evaporation having a good
10 straight-in effect, and oxidation was thereafter performed at 350°C for 30 minutes.

This step was followed by the same steps as those in the first embodiment.

The above-described device arrangement enabled
15 formation of a finer gap such that electrons were effectively emitted at a lower voltage of about 6 V.

Because the height of the electron-emitting material 4 (film thickness) was increased relative to that of the gate electrode, electrons were drawn out
20 not only from the upper portion of the electron-emitting material 4 but also from an intermediate portion. Thus, the arrangement in this embodiment has the effect of preventing a reduction in efficiency due to impingement of electrons on the gate electrode and
25 occurrence of a beam-thickening phenomenon.

(Embodiment 5)

An electron source obtained by arranging a

plurality of the electron-emitting devices fabricated
the first embodiment and an image forming apparatus
using this electron source will be described with
reference to Figs. 8, 9, and 10. In Fig. 8 are
5 illustrated an electron source substrate 81, X-
direction wiring 82, Y-direction wiring 83, electron-
emitting devices 84 in accordance with the present
invention, and connecting conductors 85.

The electron source with matrix wiring shown in
10 Fig. 8, in which the device capacitance is increased by
arranging a plurality of electron-emitting devices, has
a problem that, even when a short pulse produced by
pulse-width modulation is applied, the waveform is
dulled or distorted by capacitive components to cause
15 failure to obtain the necessary grayscale level, for
example. In this embodiment, therefore, a structure is
adopted in which an interlayer insulating layer is
provided by the side of the electron-emitting region to
limit the increase in capacitive components in regions
20 other than the electron-emitting region.

Referring to Fig. 8, X-direction wiring 82 has m
conductors DX1, DX2, ... DXm, which has a thickness of
about 1 μm and a width of 300 μm , and which is formed
of an aluminum wiring material by evaporation. The
25 material, film thickness, and width of the wiring
conductors are selected according to a suitable design.
Y-direction wiring 83 has n conductors DY1, DY2, ...

DYn, which has a thickness of 5 μm and width of 100 μm , and which is formed in the same manner as X-direction wiring 82. An interlayer insulating layer (not shown) is provided between the m conductors of X-direction wiring 82 and the n conductors of Y-direction wiring 83 to electrically separate these conductors (each of m and n is a positive integer).

The interlayer insulating layer (not shown) is, for example, a SiO_2 layer formed by sputtering or the like and having a thickness of about 0.8 μm . For example, the interlayer insulating film is formed in the desired shape over the whole or part of the surface of the substrate 81 on which X-direction wiring 82 has been formed. Specifically, the thickness of the interlayer insulating film is determined so as to ensure withstanding against the potential difference at the intersections of the conductors of X-direction wiring 82 and Y-direction wiring 83. The conductors of X-direction wiring 82 and Y-direction wiring 83 are respectively extended outward as external terminals.

Pairs of electrodes (not shown) constituting electron-emitting devices 84 are electrically connected to the m conductors of X-direction wiring 82 and the n conductors of Y-direction wiring 83 by connecting conductors 85 made of a conductive metal or the like.

A scanning signal application means (not shown) for applying scanning signals for selecting the rows of

electron-emitting devices 84 arranged in the X-direction is connected to X-direction wiring 82. On the other hand, a modulation signal generation means for modulating voltages applied to the columns of
5 electron-emitting devices 84 arranged in the Y-direction according to input signals is connected to Y-direction wiring 83. The drive voltage applied to each electron-emitting device is supplied as a voltage corresponding to the difference between the scanning
10 signal and the modulation signal applied to the element. In the present invention, Y-direction wiring 83 is connected to the gate electrodes 2 of the electron-emitting devices described above with respect to the first embodiment, while X-direction wiring is
15 connected to the cathodes 3 of the elements. This connection realizes a beam convergence effect which characterizes the present invention.

In the above-described arrangement, each element can be selected by using the passive-matrix wiring to
20 be driven independently.

An image forming apparatus constructed by using an electron source having such a passive matrix array will be described with reference to Fig. 9. Fig. 9 is a diagram showing the display panel of the image forming
25 apparatus.

Referring to Fig. 9, the electron source having the plurality of electron-emitting devices described

above with reference to Fig. 8 is provided on an
electron source substrate 81. The substrate 81 is
fixed on a rear plate 91. A face plate 96 has a glass
substrate 93, a phosphor film 94 provided as a light
5 emitting member on the internal surface of the glass
substrate 93, a metal back 95, etc. The rear plate 91
and the face plate 96 are connected to a supporting
frame 92 by using frit glass or the like. An envelop
97 is formed by being seal-bonded by baking in a vacuum
10 at about a temperature of 450°C for 10 minutes. The
electron-emitting devices 84 correspond to the
electron-emitting regions shown in Fig. 9. X-direction
wiring 82 and Y-direction wiring 83 are connected to
the pairs of electrodes of the electron-emitting
15 elements in this embodiment.

The envelop 97, as described above, is constituted
by the face plate 96, the supporting frame 92, and the
rear plate 91. A supporting member (not shown) called
a spacer is provided between the face plate 96 and the
20 rear plate 91 to enable the envelop 97 to have a
sufficiently high strength for resisting atmospheric
pressure.

After fabrication of the phosphor film, the metal
back 95 is made by smoothing the inner surface of the
25 phosphor film (ordinarily called "filming") and by
thereafter depositing Al by vacuum evaporation or the
like.

The face plate 96 further has a transparent electrode (not shown) provided on outer surface of the phosphor film 94 to improve the conductivity of the phosphor film 94.

5 The scanning circuit 102 will be described. The scanning circuit 102 includes M switching devices (schematically shown as S1 to Sm in the figure). Each of the switching devices S1 to Sm selects one of the output voltage from a direct-current voltage source Vx
10 and 0 (V) (ground level). The switching devices S1 to Sm are respectively connected to terminals Dx1 to DxM of the display panel 101. Each of the switching devices S1 to Sm operates on the basis of a control signal Tscan output from a control circuit 103, and may
15 be a combination of a switching device such as a field-effect transistor (FET) and other components. In this example, the direct-current voltage source Vx is configured to output a constant voltage such that the drive voltage to be applied to a device which is
20 not scanned on the basis of characteristics of the electron-emitting device (electron emitting threshold value voltage), is not higher than the electron-emitting threshold value voltage.

 The control circuit 103 has the function of
25 matching the operations of the components with each other to suitably perform display on the basis of input signals externally supplied. The control circuit 103

generates control signals Tscan, Tsft, and Tmry to the components on the basis of sync signal Tsync supplied from a sync signal separation circuit 106.

5 The sync signal separation circuit 106 is a
circuit for separating sync signal components and
luminance signal components from an NTSC television
signal externally supplied. This circuit can be formed
by using an ordinary frequency separation (filter)
circuit, etc. The sync signal separated by the sync
10 signal separation circuit 106 is formed of a vertical
sync signal and a horizontal sync signal. However, it
is shown as Tsync in the figure for convenience sake.
Image luminance signal components separated from the
television signal are shown as DATA signal for
15 convenience sake. The DATA signal is input to a shift
register 104.

 The shift register 104 is a device for serial to
parallel conversion, with respect to each image line,
of the DATA signal which is input in time sequence.
20 The shift register 104 operates on the basis of control
signal Tsft supplied from the control circuit 103.
(That is, control signal Tsft may be considered to be a
shift clock for the shift register.) Data
corresponding to one image line after serial to
25 parallel conversion (corresponding to data for driving
N electron-emitting devices) is output as N parallel
signals Id1 to Idn from the shift register 104.

The line memory 105 is a storage device for storing data corresponding to one image line for a necessary time period. The line memory 105 stores the contents of the signals I_{d1} to I_{dn} according to control
5 signal T_{mry} supplied from the control circuit 103. The stored contents are output as I'_{d1} to I'_{dn} to be input to a modulation signal generator 107.

The modulation signal generator 107 is a signal source for suitably modulating signals for driving the
10 electron-emitting devices according to image data items I'_{d1} to I'_{dn} . Output signals from the modulation signal generator 107 are applied to the electron-emitting devices in the display panel 111 through terminals Do_{y1} to Do_{yn} .

15 As described above, each electron-emitting device to which the present invention can be applied has basic characteristics described below with respect to emission current I_e . That is, there is a definite threshold value voltage V_{th} with respect to emission of
20 electrons. Emission of electrons is caused only when a voltage higher than V_{th} is applied. When a voltage higher than the electron emission threshold value is applied to the electron-emitting device, the emission current changes according to changes in the applied
25 voltage. Therefore, in a case where a voltage in the form of pulses is applied to the electron-emitting device, electron emission is not caused when the value

of the applied voltage is lower than the electron emission threshold value, but an electron beam is output when the value of the applied voltage is equal to or higher than the electron emission threshold value. In this case, the strength of the electron beam can be controlled by changing the pulse crest value V_m . Also, the total amount of charge of the output electron beam can be controlled by changing the pulse width P_w .

Therefore, a voltage modulation method, a pulse-width modulation method or the like can be used as a method for modulating the electron-emitting device according to the input signal. If the voltage modulation method is carried out, a voltage modulation type of circuit capable of generating voltage pulses having a constant duration, and modulating the pulse crest value according to input data may be used as modulation signal generator 107.

If the pulse-width modulation method is carried out, a pulse-width modulation type of circuit capable of generating voltage pulses having a constant crest value and modulating the pulse width of the voltage pulses according to input data may be used as modulation signal generator 107.

Each of the shift register 104 and the line memory 105 used in this embodiment is of a digital signal type.

In this embodiment, a digital to analog converter

circuit, for example, is used in the modulation signal generator 107 and an amplifier circuit, etc., are added if necessary. For example, in the case where the pulse-width modulation method is used, a combination of
5 a high-speed oscillator, a counter for counting the number of waves output from the oscillator, and a comparator for comparing the output value of the counter and the output value of the above-described memory is used in the modulation signal generator 107.

10 The configuration of the image forming apparatus described above is an example of the image forming apparatus to which the present invention can be applied. Various modifications and changes can be made therein on the basis of the technical spirit of the
15 present invention. The input signal is not limited to the above-mentioned NTSC signal. Those in accordance with the PAL system and the SECAM system and other TV signals corresponding to a larger number of scanning lines (e.g., those for the MUSE system and other high-
20 definition TV systems) may also be used.

Images were displayed on an image display apparatus made in accordance with this embodiment. High-luminance high-definition images had been
displayed on the image display apparatus with stability
25 for a long period of time.

According to the present invention, as described above, the specific capacitance of an electron-emitting

device can be reduced and the drive voltage can also be reduced. An electron source having improved efficiency and a smaller beam size can be realized by using such an electron-emitting device.

- 5 An image forming apparatus having high resolution, e.g., a color flat-screen television can be realized by using the electron-emitting device in accordance with the present invention.

WHAT IS CLAIMED IS:

1. An electron-emitting apparatus comprising:

A) a first electrode and a second electrode
disposed on a surface of a substrate;

5 B) first voltage application means for applying to
said second electrode a potential higher than a
potential applied to said first electrode;

C) an electron-emitting member disposed on said
first electrode;

10 D) a third electrode disposed so as to face said
substrate, electrons emitted from said electron-
emitting member reaching said third electrode; and

E) second voltage application means for applying
to said third electrode a potential higher than each of
15 the potentials applied to said first and second
electrodes,

wherein a surface of said electron-emitting member
is placed between a plane containing a surface of said
second electrode and substantially parallel to the
20 surface of said substrate and a plane containing a
surface of said third electrode and substantially
parallel to the surface of said substrate, and

wherein when the distance between said second
electrode and said first electrode is d ; the potential
25 difference applied between said second electrode and
said first electrode by said first voltage application
means is V_1 ; the distance between said third electrode

and said substrate is H; and the potential difference
between the potential applied to said third electrode
by said second voltage application means and the
potential applied to said first electrode by said first
5 voltage application means is V2, then an electric field
 $E1 = V1/d$ is within the range from 1 to 50 times an
electric field $E2 = V2/H$.

2. An apparatus according to claim 1, wherein the
10 thickness of said first electrode is larger than the
thickness of said second electrode.

3. An apparatus according to claim 1, wherein
said electron-emitting member extends from a position
15 on said first electrode to a position on said substrate
between said first electrode and said second electrode.

4. An apparatus according to claim 1, wherein
said substrate has a difference in level between said
20 second electrode and said first electrode, and said
third electrode is closer to said first electrode than
to said second electrode.

5. An apparatus according to claim 1, wherein
25 said electron-emitting member is made of a material
containing carbon as a main ingredient.

6. An apparatus according to claim 5, wherein said material containing carbon as a main ingredient comprises fibrous carbon.

5 7. An apparatus according to claim 6, wherein said fibrous carbon comprises a graphite nanofiber, a carbon nanotube, amorphous carbon, or a mixture of at least two of these materials.

10 8. An apparatus according to claim 7, wherein said fibrous carbon is grown by means of catalytic particles.

 9. An apparatus according to claim 8, wherein
15 catalytic particles are made of Pd, Ni, Fe, Co or an alloy of at least two of these metals.

 10. An apparatus according to any one of claims 1
to 9, wherein a plurality of said first electrodes and
20 a plurality of said second electrodes are disposed on the surface of said substrate.

 11. An apparatus according to claim 10, wherein
said plurality of first electrodes and said plurality
25 of second electrodes are electrically connected to wiring in matrix form.

12. An apparatus according to claim 10, wherein a phosphor capable of emitting light when irradiated with electrons emitted from said electron-emitting member is provided on said third electrode.

5

13. An image display apparatus using an electron-emitting apparatus according to claim 12.

14. An electron-emitting device comprising:

10 A) a fiber containing carbon as a main ingredient;
and

 B) an electrode for controlling emission of electrodes from said fiber containing carbon as a main ingredient,

15 wherein said fiber containing carbon as a main ingredient has a plurality of graphenes layered so as not to be parallel to the axis direction of said fiber.

20 15. An electron-emitting device according to claim 14, wherein the plurality of graphenes are substantially parallel to each other.

25 16. An electron-emitting device according to claim 14, further comprising a cathode, wherein said fiber containing carbon as a main ingredient is provided on said cathode and is electrically connected to said cathode.

17. An electron-emitting device according to
claim 16, wherein said cathode and said electrode for
controlling emission of electrons are disposed on one
substrate, a gap being formed between said cathode and
5 said electrode for controlling emission of electrons.

18. An electron-emitting device according to
claim 14, wherein said electron-emitting device
comprises a plurality of said fibers containing carbon
10 as a main ingredient.

19. A light-emitting apparatus comprising an
electron-emitting device according to any one of claims
14 to 18, and a light-emitting member.

15

20. An image display apparatus comprising a
plurality of electron-emitting devices and a light
emitting member capable of emitting light when
irradiated with electrons emitted from some of said
20 plurality of electron-emitting devices, wherein each of
said plurality of electron-emitting devices is
constituted by the electron-emitting device according
to any one of claims 14 to 18.

25 21. An electron-emitting apparatus comprising:
A) a first electrode and a second electrode
disposed on a surface of a substrate;

B) first voltage application means for applying to said second electrode a potential higher than a potential applied to said first electrode;

5 C) a plurality of fibers disposed on said first electrode, said fibers containing carbon as a main constituent;

D) a third electrode disposed so as to face said substrate, electrons emitted from said fibers reaching said third electrode; and

10 E) second voltage application means for applying to said third electrode a potential higher than each of the potentials applied to said first and second electrodes,

15 wherein a surface region of said fibers is placed between a plane containing a surface of said second electrode and substantially parallel to the surface of said substrate and a plane containing a surface of said third electrode and substantially parallel to the surface of said substrate.

20

22. An electron-emitting apparatus according to claim 21, wherein when the distance between said second electrode and said first electrode is d ; the potential difference applied between said second electrode and
25 said first electrode by said first voltage application means is V_1 ; the distance between said third electrode and said substrate is H ; and the potential difference

between the potential applied to said third electrode
by said second voltage application means and the
potential applied to said first electrode is V_2 , then
an electric field $E_1 = V_1/d$ is within the range from 1
5 to 50 times an electric field $E_2 = V_2/H$.

23. An apparatus according to claim 21, wherein
each of said fibers having carbon as a main ingredient
comprises a carbon nanotube.

10

24. An apparatus according to claim 21, wherein
each of said fibers containing carbon as a main
ingredient comprises a plurality of graphenes stacked
so as to be nonparallel to the axis direction of said
15 fiber.

25. An apparatus according to claim 21, wherein a
material more effective in accelerating deposition of
carbon than the material of said first electrode is
20 provided between said fibers having carbon as a main
ingredient and said cathode.

26. An apparatus according to claim 25, wherein
said material effective in accelerating deposition of
25 carbon comprises Pd, Ni, Fe, Co or an alloy formed of
at least two of said metals.

27. An apparatus according to claim 25, wherein said material effective in accelerating deposition of carbon is provided in the form of a plurality of particles on said first electrode.

5

28. An apparatus according to claim 27, wherein said plurality of particles are provided on said first electrode at a density of 10^{10} particles/cm² or higher.

10

29. An apparatus according to claim 21, wherein the thickness of said first electrode is larger than the thickness of said second electrode.

15

30. An apparatus according to any one of claims 21 to 29, wherein a plurality of said first electrodes and a plurality of said second electrodes are disposed on the surface of said substrate.

20

31. An apparatus according to claim 30, wherein said plurality of first electrodes and said plurality of second electrodes are electrically connected to wiring in matrix form.

25

32. An apparatus according to claim 30, wherein a phosphor capable of emitting light when irradiated with electrons emitted from said fibers is provided on said third electrode.

33. An image display apparatus using an electron-emitting apparatus according to claim 32.

34. An electron-emitting device comprising:

- 5 A) a first electrode and a second electrode
disposed on a surface of a substrate, a gap being
formed between said first and second electrodes; and
B) a fiber provided on said first electrode, said
fiber containing carbon as a main ingredient,
10 wherein said second electrode comprises an
electrode for controlling emission of electrodes from
said fiber containing carbon as a main ingredient, and
wherein said fiber containing carbon as a main
ingredient comprises graphene.

15

35. An electron-emitting device according to
claim 34, wherein the distance between an extreme end
of said fiber and the surface of said substrate is
larger than the distance between the surface of said
20 second electrode and the surface of said substrate.

36. An electron-emitting device according to
claim 34, wherein said graphene comprises cylindrical
graphene.

25

37. An electron-emitting device according to
claim 34, wherein said electron-emitting device

comprises a plurality of fibers containing carbon as a main ingredient.

38. A light-emitting apparatus comprising an
5 electron-emitting device according to any one of claims 34 to 37, and a light-emitting member.

39. An image display apparatus comprising a
plurality of electron-emitting devices and a light
10 emitting member capable of emitting light when irradiated with electrons emitted from some of said plurality of electron-emitting devices, wherein each of said plurality of electron-emitting devices is constituted by an electron-emitting device according to
15 any one of claims 34 to 37.

ABSTRACT OF THE DISCLOSURE

An electron-emitting device in which the specific capacitance and the drive voltage are reduced, and which is capable of obtaining a finer electron beam by controlling the trajectory of emitted electrons. An electron-emitting portion of an electron-emitting member is positioned between the height of a gate and the height of an anode. When the distance between the gate and a cathode is d ; the potential difference at driving the device is V_1 ; the distance between the anode and the substrate is H ; and the potential difference between the anode and the cathode is V_2 , then the electric field $E_1 = V_1/d$ during driving is configured to be within the range from 1 to 50 times $E_2 = V_2/H$.

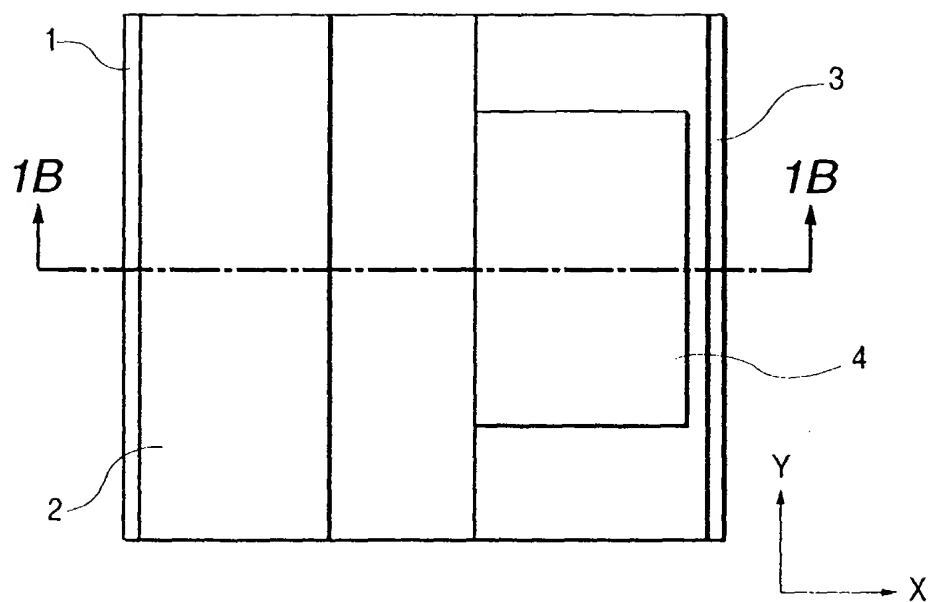
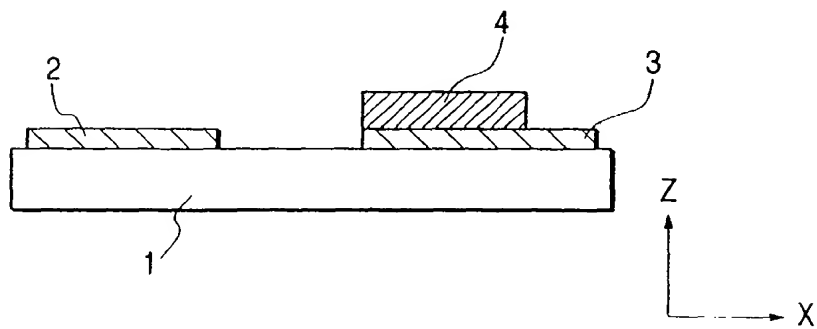
FIG. 1A*FIG. 1B*

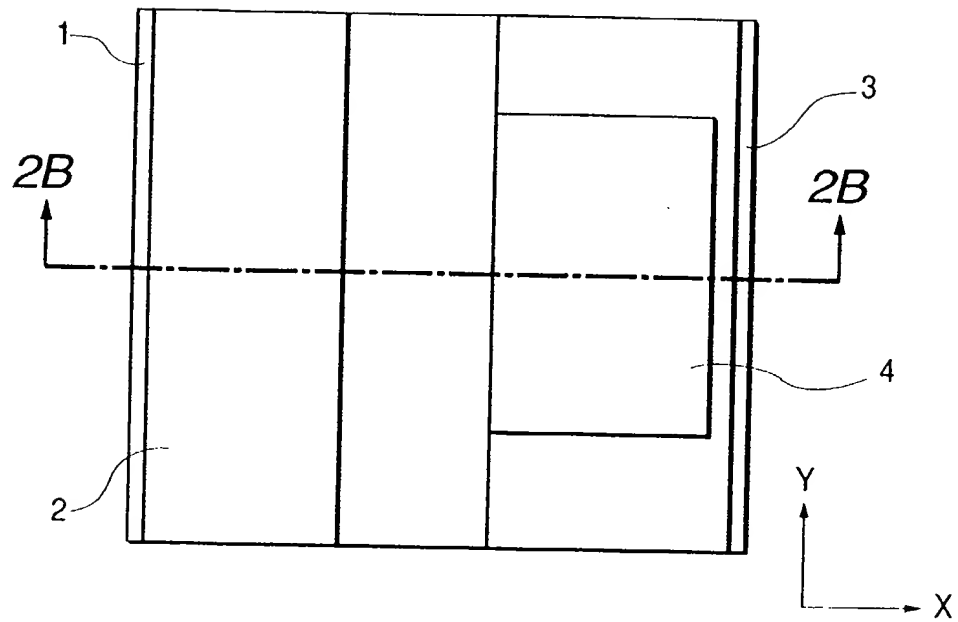
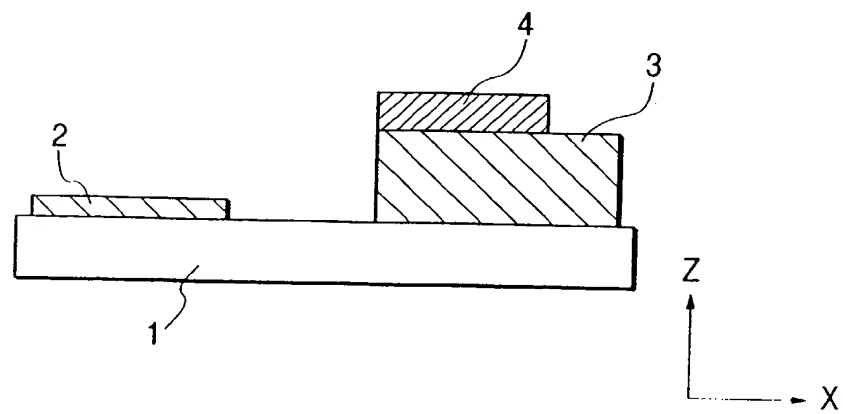
FIG. 2A*FIG. 2B*

FIG. 3A

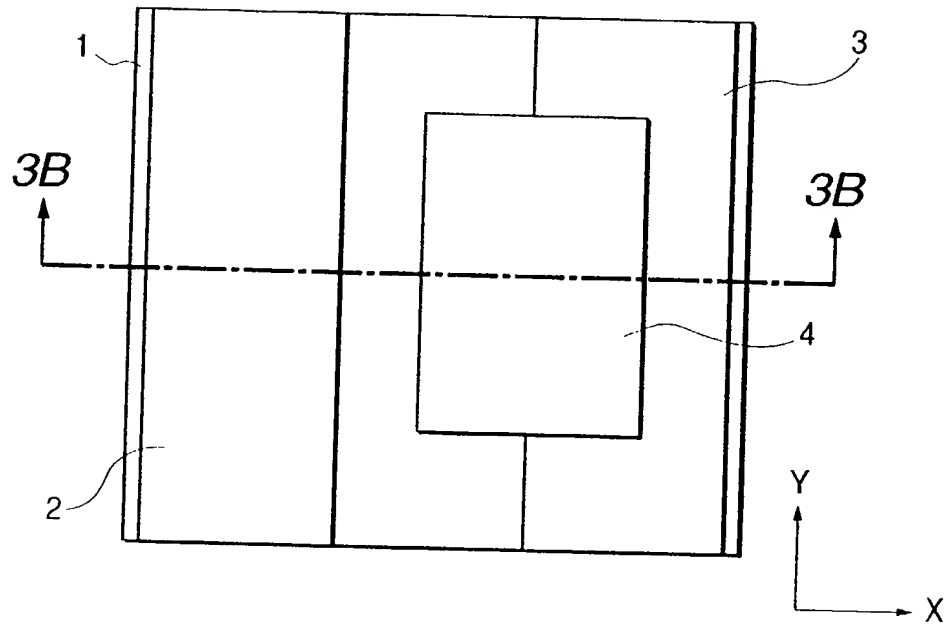


FIG. 3B

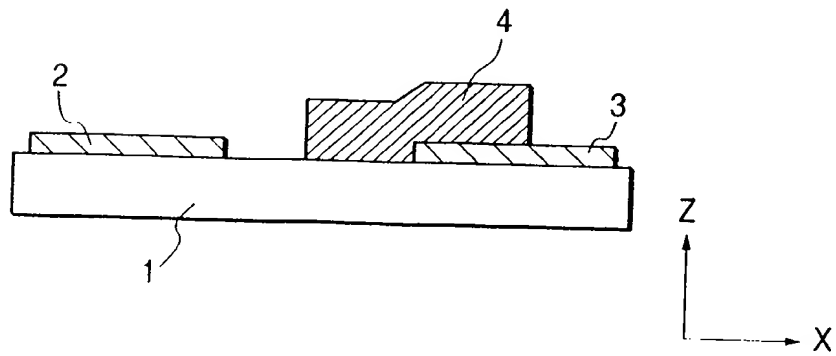


FIG. 4A

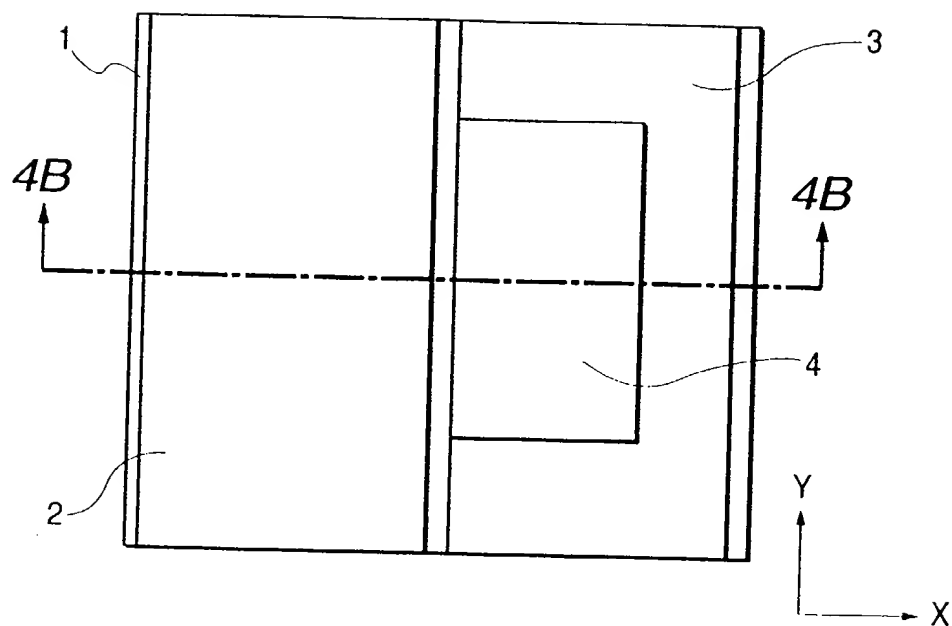


FIG. 4B

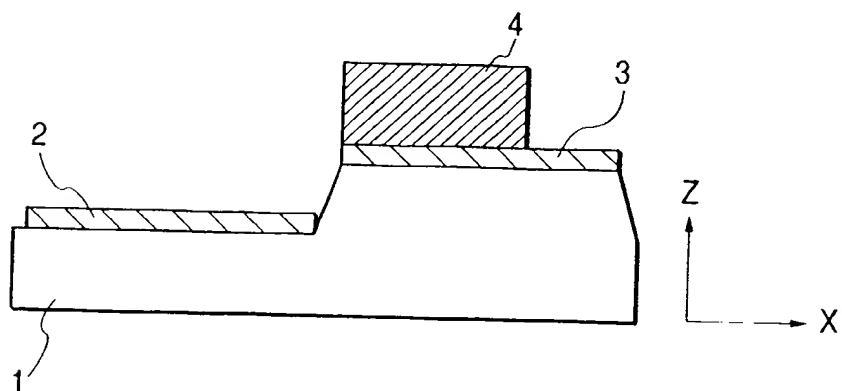


FIG. 5A

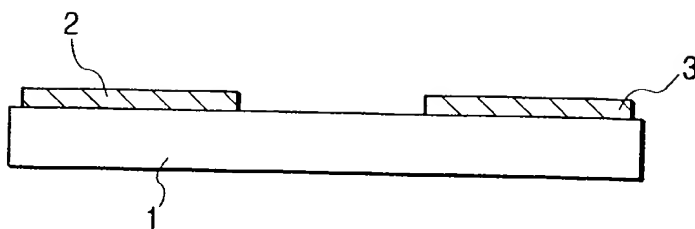


FIG. 5B

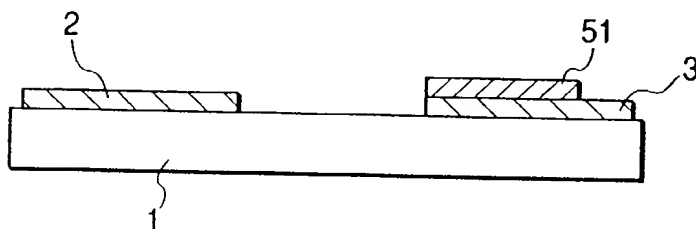


FIG. 5C

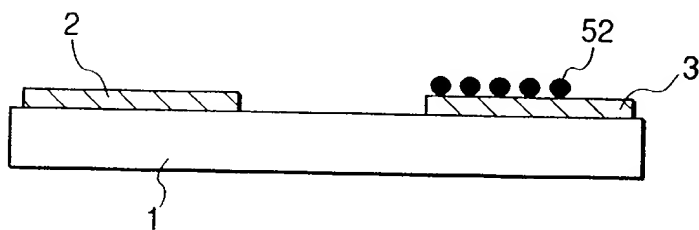


FIG. 5D

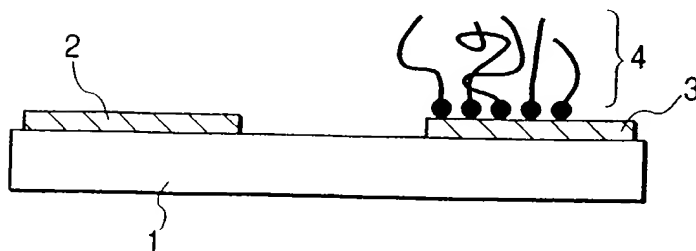


FIG. 6

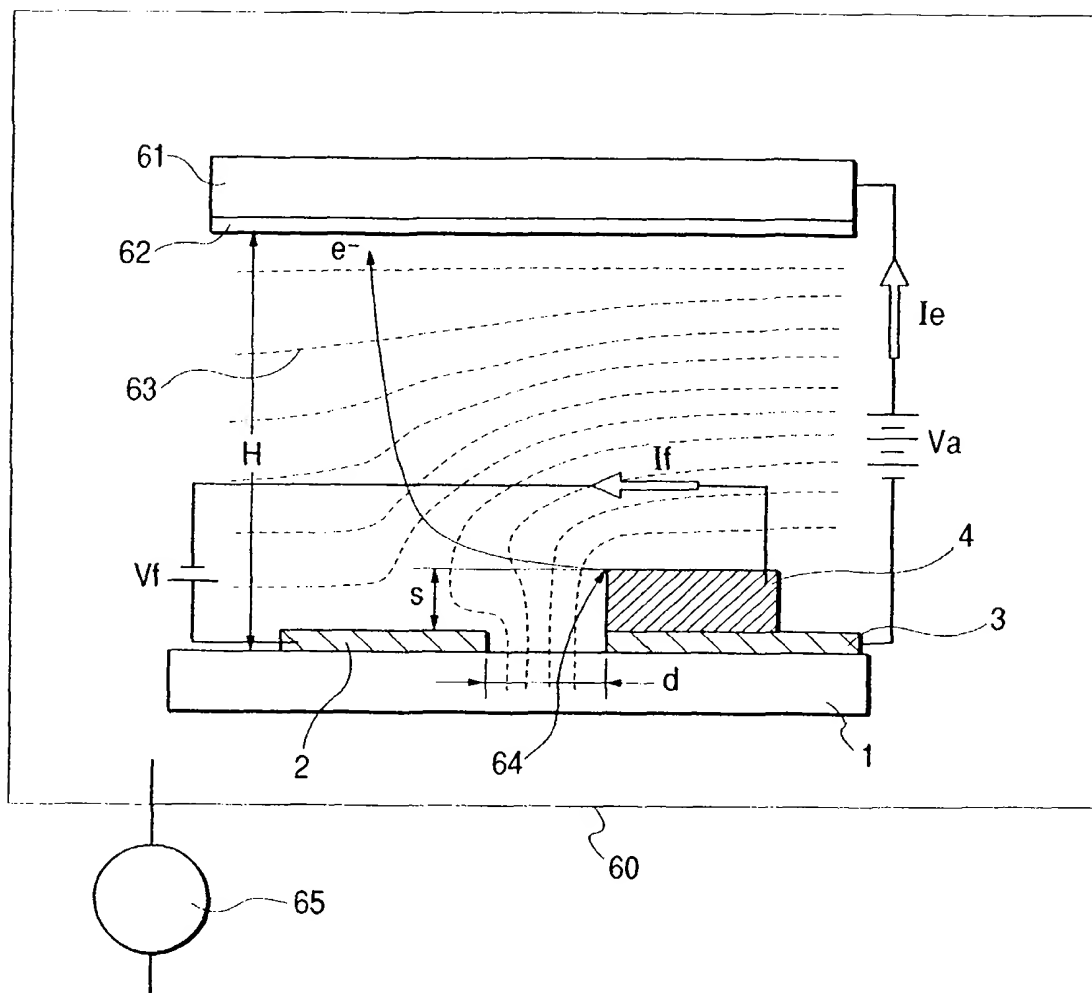


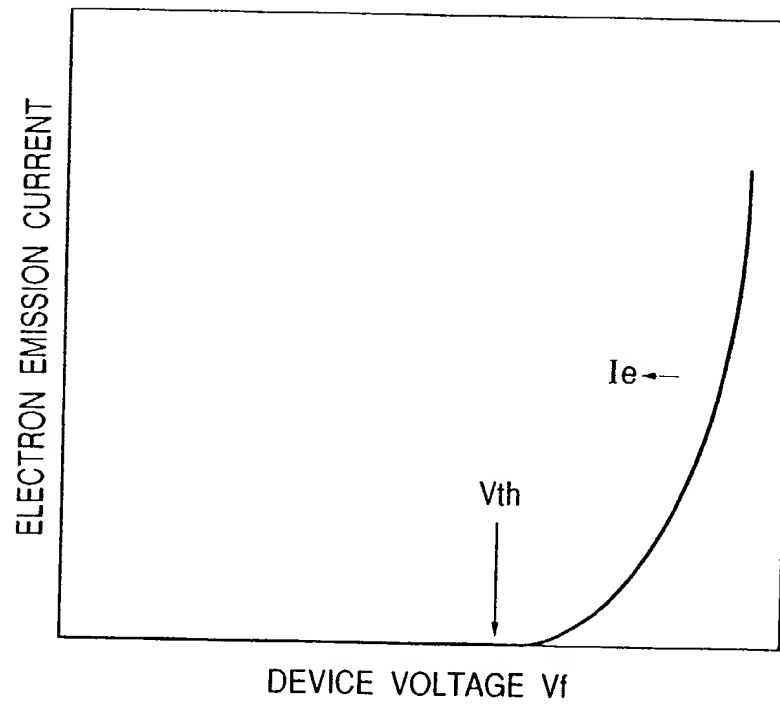
FIG. 7

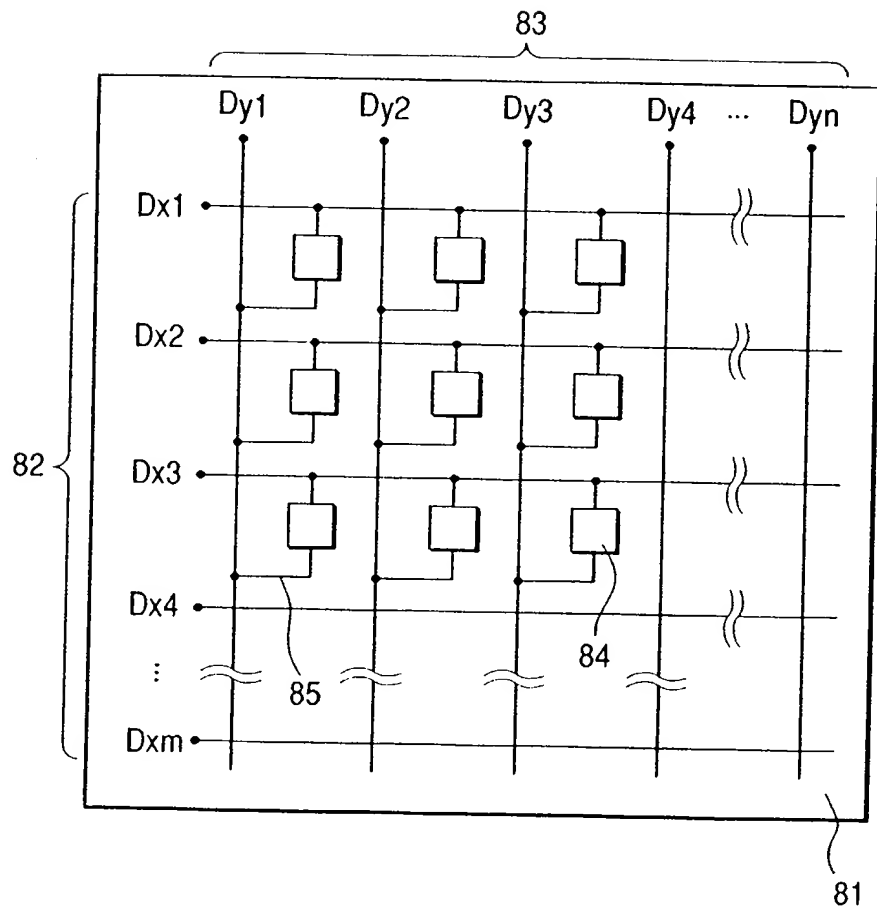
FIG. 8

FIG. 9

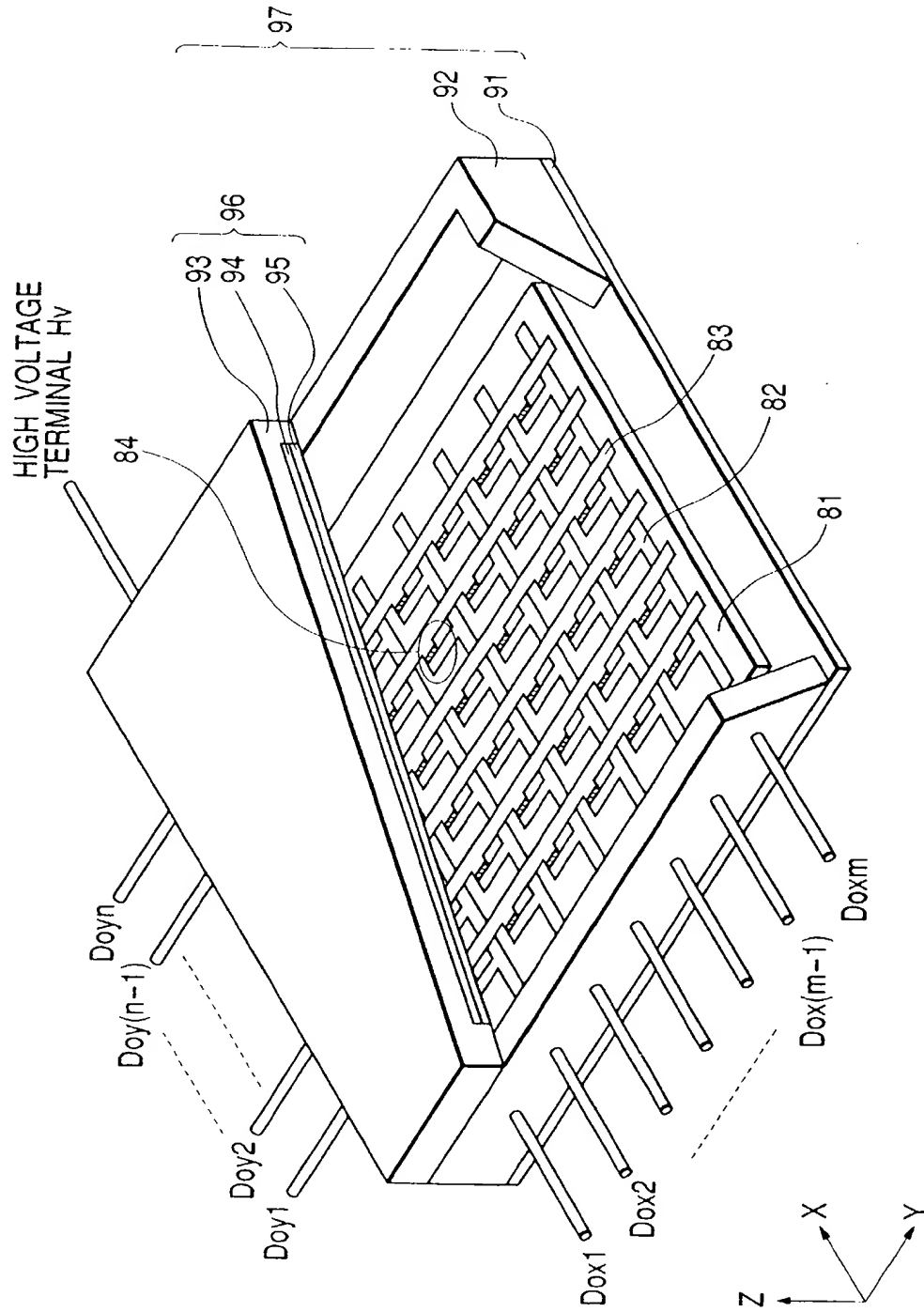


FIG. 10

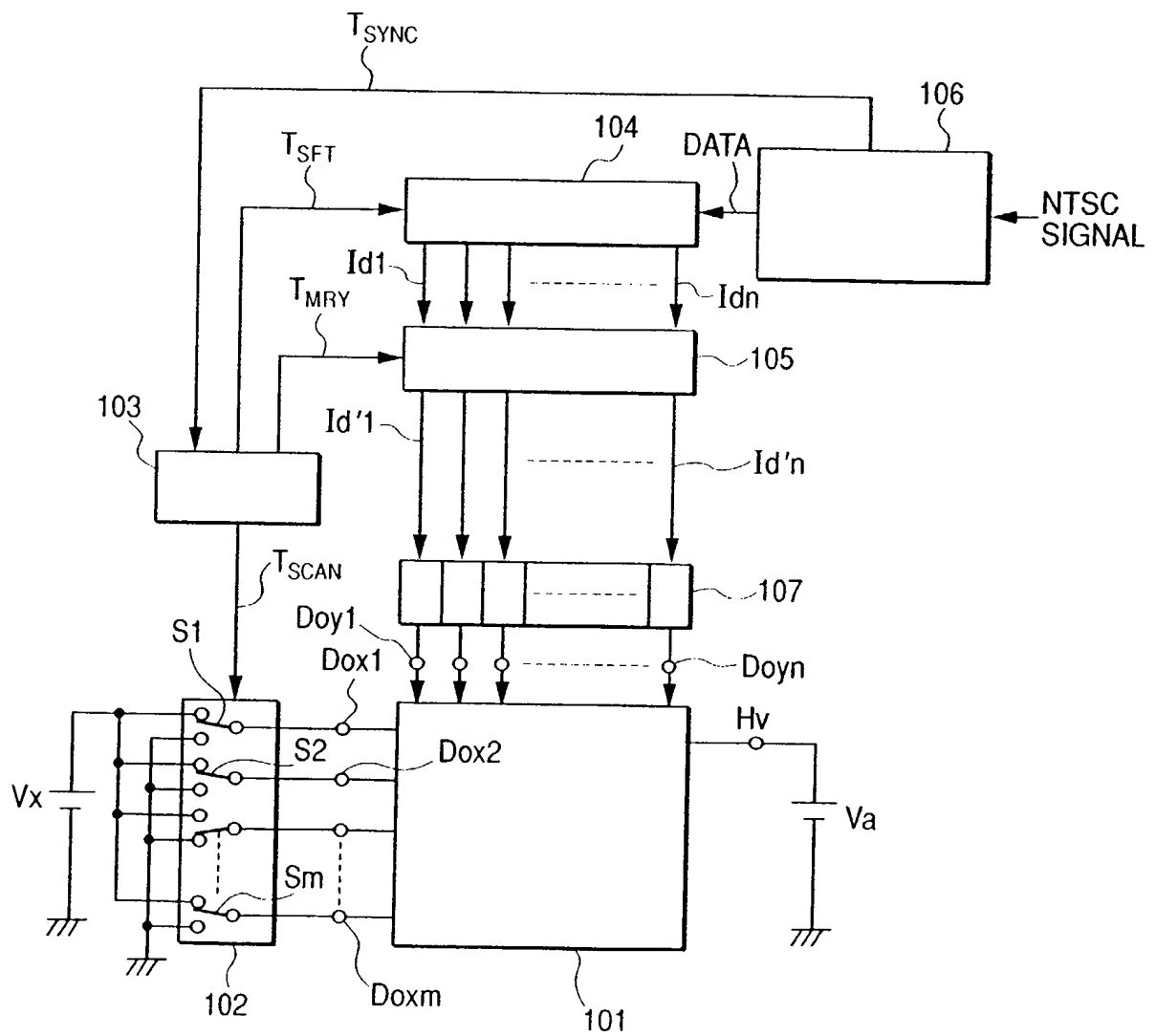


FIG. 11

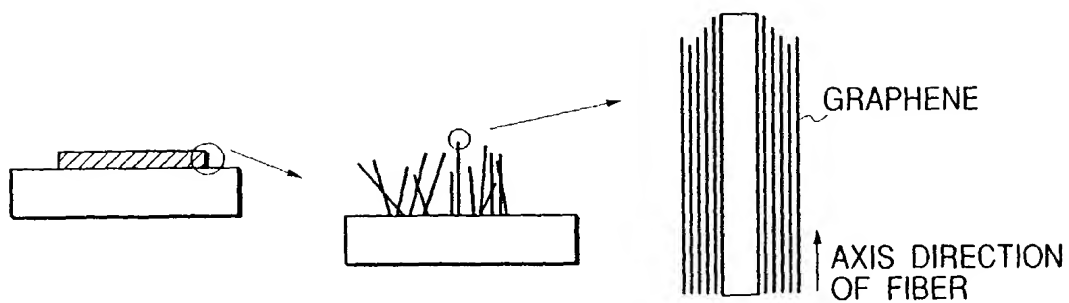


FIG. 12

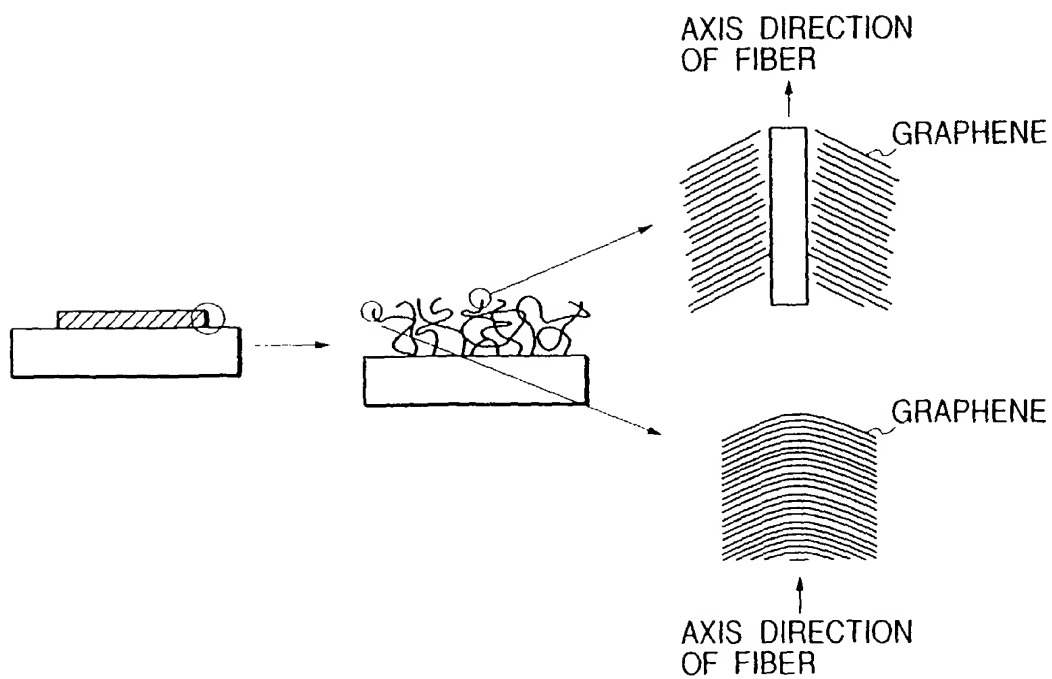


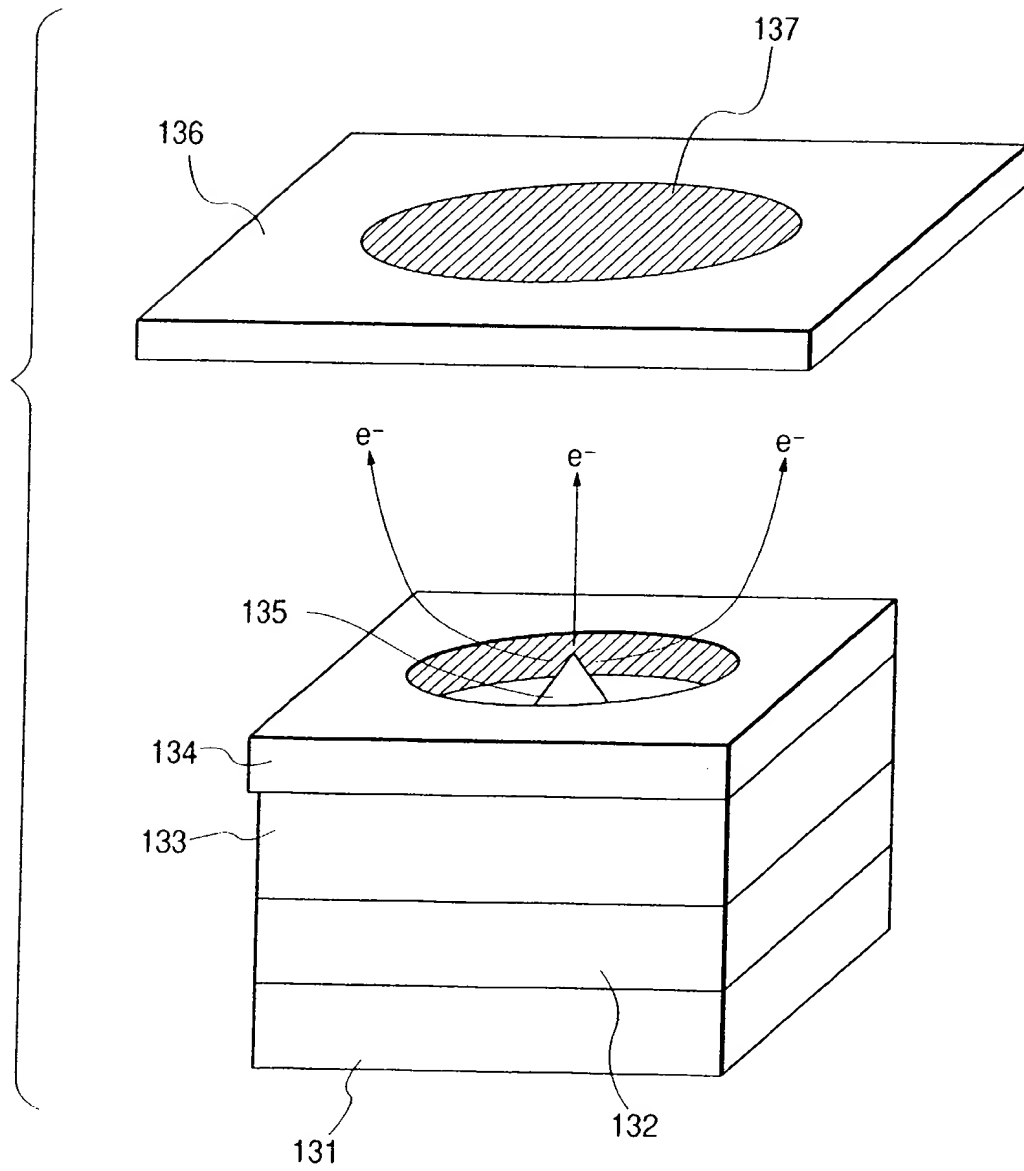
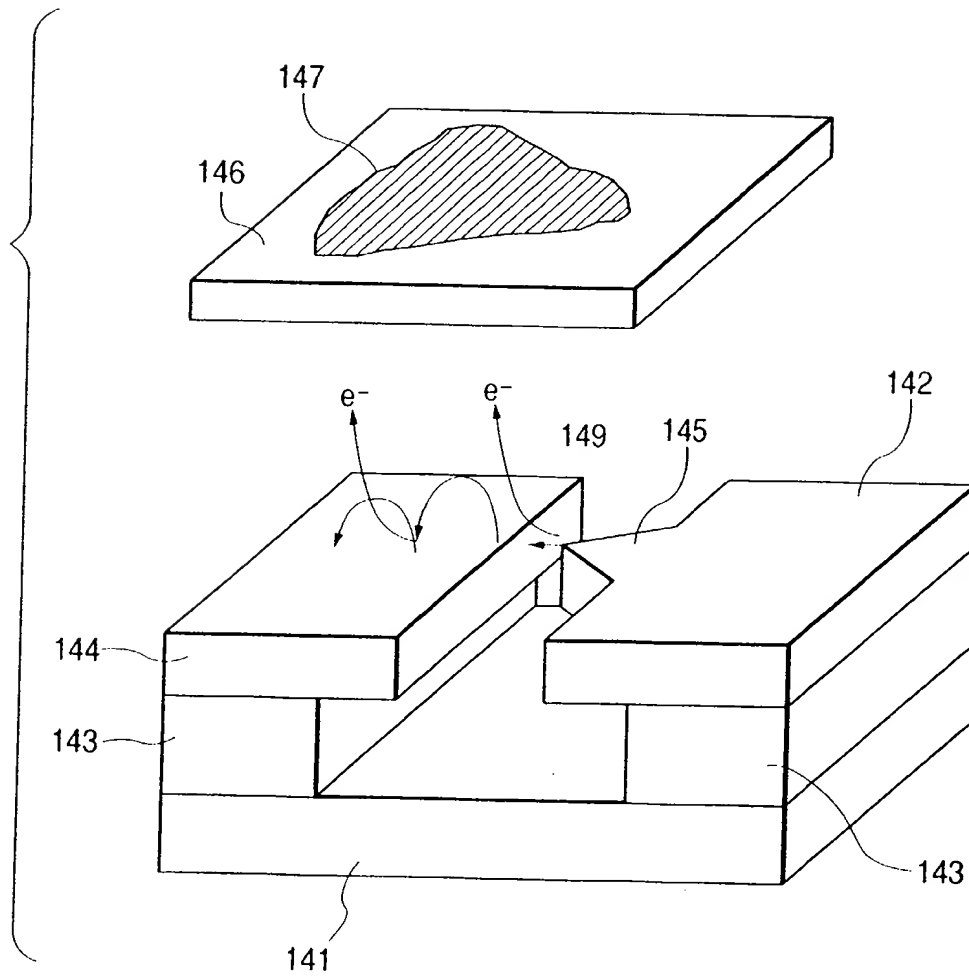
FIG. 13

FIG. 14

ELECTRON-EMITTING DEVICES, ELECTRON SOURCES, GAU 2879
AND IMAGE-FORMING APPARATUS



BACKGROUND OF THE INVENTION

5 Field of the Invention

The present invention relates to electron-emitting devices for emission of electrons, electron sources using them, and image-forming apparatus using the electron sources. The image-forming apparatus according to the present invention can be used in display devices for television broadcasting and the like, display devices of video conference systems, computers, etc., optical printers constructed with use of a photosensitive drum or the like, and so on.

15 Related Background Art

Conventionally, field emission type (FE type) electron-emitting devices configured to apply a strong electric field of not less than 10^6 V/cm to metal and thereby emit electrons from the metal surface are drawing attention as one of cold electron sources.

If such FE type cold electron sources become practically available, it will become feasible to construct low-profile emissive type image display devices and they will also contribute to reduction in power consumption and reduction in weight.

Known as an example of a vertical FE type is a device in which, as shown in Fig. 13, an emitter 135 is

of the shape of a circular cone or a quadrangular
pyramid formed from a substrate 131 approximately in
the vertical direction; for example, one disclosed in
C. A. Spindt, "Physical Properties of thin-film field
5 emission cathodes with molybdenum cones," J. Appl.
Phys., 47, 5248 (1976) or the like (hereinafter
referred to as a Spindt type).

On the other hand, a lateral FE structure is shown
in Fig. 14. In the figure, numeral 141 designates a
10 substrate, 142 an emitter electrode, 143 an insulating
layer, 145 an emitter, 146 an anode, and 147 a profile
of an electron beam irradiating the anode. The emitter
145 sharp-pointed at the tip is arranged in parallel
with a gate electrode 144 for extracting electrons from
15 the emitter tip, on the substrate and the collector
(anode electrode) is disposed above the substrate on
which the gate electrode and the emitter electrode are
placed (see USP No. 4,728,851, USP No. 4,904,895, and
so on).

20 As an example of the electron-emitting devices
using fibrous carbon, Japanese Patent Application Laid-
Open No. 8-115652 discloses a configuration in which
thermal decomposition is implemented in the presence of
organic compound gas on fine particles of catalyst
25 metal whereby fibrous carbon is deposited in a fine
gap.

As electroconductive layers for carbon nanotubes,

Japanese Patent Application Laid-Open No. 11-194134 and European Patent EP0913508A2 describe metal layers of titanium (Ti), zirconium (Zr), niobium (Nb), tantalum (Ta), and molybdenum (Mo). Japanese Patent Application
5 Laid-Open No. 11-139815 describes Si as an electroconductive substrate.

The beam profiles of the electron-emitting devices according to the prior arts will be described referring to Figs. 13 and 14.

10 In Fig. 13, which shows the Spindt type electron-emitting device according to the foregoing prior art, numeral 131 denotes the substrate, 132 the emitter electrode, 133 the insulating layer, 134 the gate, and 135 the emitter connected to the emitter electrode 132.
15 When V_f is placed between the emitter 135 and the gate 134, the electric field becomes stronger at the tip of the projection of the emitter 135 and then electrons are emitted from the vicinity of the tip of the cone into the vacuum.

20 Since the electric field at the tip of the emitter is formed in such a certain finite area as to follow the shape of the emitter tip, the extracted electrons are drawn in the vertical direction relative to the potential from the finite area at the emitter tip.

25 At this time, electrons are also emitted at various angles. As a result, electrons with large angle components are drawn in directions toward the

internal peripheral surface in the hole formed in the gate 134.

As a consequence, where the hole is circular, an electron distribution obtained on the anode 136 in the figure becomes a substantially circular beam profile 137. This indicates that the resultant beam profile is in close relation with the shape of the gate and the distance to the emitter.

The lateral FE configuration as shown in Fig. 14 is the prior art in which electrons are emitted in the aligned extraction direction.

In Fig. 14, numeral 141 designates the substrate, 142 the emitter electrode, 143 the insulating layer, 144 the gate, and 145 the emitter, and the anode 146 is provided on a substrate opposed to the substrate on which the emitter and gate are disposed.

In the case of the lateral FE configuration constructed in this way, some of electrons emitted from the emitter 145 are extracted (or emitted) into the vacuum, but the rest are taken into the gate 144.

In the configuration shown in Fig. 14, the direction of the electric field vector for emission of electrons (the electric field from the emitter 145 toward the gate 144) is different from the direction of the electric field vector toward the anode 146. As a result, the electron distribution (electron beam spot) becomes large.

SUMMARY OF THE INVENTION

The prior arts as described above had the following problems.

5 Since in the foregoing Spindt type the gate and the substrate were constructed in the layered structure, a large gate capacitance and a lot of parasitic capacitances to the emitter were made. Further, the driving voltage was as high as several ten volts, and there was the drawback of large capacitive
10 power consumption because of the configuration. The Spindt type configuration also had the problem that the beam profile became expanded at the positive electrode (anode).

The foregoing lateral FE configuration had the
15 advantage of capability of reducing the capacitance of the device but had the disadvantage of increasing the driving voltage, because the large distance between the emitter and the gate required several hundred volts for driving. This configuration also had the problem that
20 the beam profile was expanded at the positive electrode (anode).

It is also conceivable to provide the above Spindt type and lateral FE type electron-emitting devices with a beam focusing means, but this raises problems of
25 complexity in a fabrication method, increase in the device area, decrease in electron emission efficiency, and so on.

The present invention has been accomplished in order to solve the above problems and an object of the invention is to provide electron-emitting devices that are reduced in the device capacitance and the driving
5 voltage and improved in the electron emission efficiency and that can provide a high-definition beam stably over a long period, and electron sources and image-forming apparatus using them.

In order to achieve the above object, an electron-
10 emitting device according to the present invention comprises a first electrode and a second electrode arranged in opposition to each other with a gap between first and second electrodes on a surface of a substrate, and a plurality of fibers electrically
15 connected to the first electrode and comprising carbon as a main component, and the fibers are placed on a surface of the first electrode facing the second electrode.

In order to achieve the above object, another
20 electron-emitting device according to the present invention comprises an extraction electrode and a cathode electrode formed in opposition to each other with a gap between the extraction electrode and the negative electrode on an electrically insulating
25 substrate, a first layer formed on the negative electrode and having an oxide of Ti, an oxide of Zr, or an oxide of Nb on a surface thereof, and a fibrous

carbon grown through a catalyst particle disposed on a side wall surface of the first layer on the extraction electrode side.

5 An electron source according to the present invention is characterized by a plurality of above-stated electron-emitting devices arrayed.

An image-forming apparatus according to the present invention is characterized by use of the above electron source.

10 According to the present invention, it is feasible to provide the electron-emitting devices presenting a small electron beam spot on the anode, achieving excellent electron emission efficiency, and having excellent durability, a small capacitance component,
15 and excellent stability. The electron sources using the electron-emitting devices can realize quick responsivity and low power consumption. The image-forming apparatus using the electron sources can provide high-definition images with high luminance over
20 a long period, in addition to the quick responsivity and low power consumption.

BRIEF DESCRIPTION OF THE DRAWINGS

25 Figs. 1A and 1B are schematic views showing an electron-emitting device according to an embodiment and Example 1 of the present invention;

Figs. 2A and 2B are schematic views showing

another electron-emitting device according to Example 2 of the present invention;

Figs. 3A and 3B are schematic views showing still another electron-emitting device according to Example 3
5 of the present invention;

Figs. 4A and 4B are schematic views showing still another electron-emitting device according to Example 4 of the present invention;

Figs. 5A, 5B, 5C, 5D and 5E are step diagrams for
10 production of the electron-emitting device according to Example 1 of the present invention;

Fig. 6 is a diagram for explaining the operation of the electron-emitting device;

Fig. 7 is a characteristic diagram of the
15 fundamental operation of the electron-emitting device;

Fig. 8 is a schematic plan view of an electron source according to an embodiment of the present invention;

Fig. 9 is a perspective view of an image-forming
20 apparatus, partly broken, according to an embodiment of the present invention;

Fig. 10 is a block diagram of an image-forming apparatus according to an embodiment of the present invention;

25 Fig. 11 is a schematic structure diagram of fibrous carbons (carbon nanotubes);

Fig. 12 is a schematic structure diagram of

fibrous carbons (graphite nanofibers);

Fig. 13 is a schematic structure diagram of the vertical FE configuration according to the prior art; and

5 Fig. 14 is a schematic structure diagram of the lateral FE configuration according to the prior art.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The embodiments of the present invention will be
10 illustratively described hereinafter in detail with reference to the drawings. It is, however, noted that, as to the dimensions, materials, shapes, relative locations, etc. of the components described in the
embodiments, the scope of the invention is by no means
15 intended to be limited only to those unless otherwise stated specifically.

The inventors conducted research on materials that permitted fine (several nm order) nuclei (catalyst particles) to be formed thereon from a catalyst and
20 that formed stable electrical coupling with fibrous carbons grown from the nuclei by thermal decomposition.

From the research, the inventor found that preferable materials permitting the growth of the fibrous carbons through the catalyst and achieving
25 electrical coupling therewith were materials selected from Ti, Zr, and Nb and oxidized in part (at the interface in contact with the fibrous carbons or the

catalyst), or oxide semiconductors of materials selected from Ti, Zr, and Nb.

5 From detailed investigation, the inventor further found that the fibrous carbons were able to be produced at the position of the catalyst particles with good repeatability, by use of a member in which the catalyst particles (particularly preferably, Pd particles) were placed on an oxide of a material selected from Ti, Zr, and Nb.

10 In tandem with it, the inventor also found that materials on which no fibrous carbon grew or on which a growth rate of fibrous carbon was low, were Ta, Cr, Au, Ag, Pt, and materials of the same kinds as the catalyst materials.

15 The growth of the fibrous carbons over these materials is also valid in the layered structure. For example, Cr was deposited over the entire surface of a substrate, a fine region of titanium oxide was further formed on the Cr layer, and the entire surface of the substrate was coated with palladium oxide. With use of
20 this substrate, the fibrous carbons were selectively grown only above titanium oxide.

Then the electron-emitting devices, electron sources, and image-forming apparatus using the fibrous
25 carbons according to the present invention, using the technology of forming the fibrous carbons at a desired position with good repeatability as described above,

will be described below in comparison with the prior art examples.

First, the inventors also conducted research about a method of forming a high-definition electron beam.
5 The high-definition beam forming method will be described below.

In general, the operating voltage V_f of the FE device is determined by the electric field at the tip portion of the emitter, which is derived by the
10 Poisson's equation, and the current density of electron emission current obtained according to a relation called the Fowler-Nordheim equation, using the electric field and a work function at the emitter portion as parameters.

15 As for the electric field necessary for the electron emission, the smaller the distance d between the emitter tip and the gate electrode, or the smaller the radius r of the emitter tip, the stronger the electric field is established.

20 On the other hand, the maximum X-directional size X_d of the electron beam on the anode (for example, the maximum range from the center of the circular beam profile 137 in Fig. 13) is expressed in the form proportional to $\sqrt{(V_f/V_a)}$ in simple computation.

25 As apparent from this relation, increase in V_f results in increase in the beam size.

From this consideration, the distance d and radius

r need to be set as small as possible in order to decrease V_f .

The beam profiles of the conventional configurations will be described below using Figs. 13 and 14. In the figures, numerals common thereto denote as follows: 131, 141 the substrate; 132, 142 the emitter electrode; 133, 143 the insulating layer; 135, 145 the emitter; 136, 146 the anode; 137, 147 the shape of the electron beam irradiating the anode.

In the case of the foregoing Spindt type, as shown in Fig. 13, when V_f is applied between the emitter 135 and the gate 134, the electric field becomes stronger at the tip of the projection of the emitter 135, and electrons are taken out from near the tip of the conical emitter into the vacuum.

Since the electric field at the tip of the emitter 135 is formed in such a certain finite area as to follow the shape of the tip of the emitter 135, electrons extracted are drawn in the vertical direction relative to the potential from the finite area of the tip of the emitter 135.

At this time, electrons are emitted at various angles and electrons with large angle components are drawn in directions toward the gate. When the gate 134 is circular, the electron distribution on the anode 136 becomes the substantially circular beam profile 137 as shown in the figure.

Namely, the resultant beam profile is in close relation with the shape of the extraction gate and the distance to the emitter.

In the case of the lateral FE configuration (Fig. 14) wherein electrons are extracted in the aligned extraction direction, the very strong electric field (lateral electric field) is created substantially in parallel to the surface of the substrate 141 between the emitter 145 and the gate 144, so that among electrons emitted from the emitter 145, some electrons 149 are drawn into the vacuum and the remaining electrons are taken into the gate electrode 144.

In the case of the configuration shown in this Fig. 14, the direction of the electric field vector for the emission of electrons (the electric field directed from the emitter 145 toward the gate 144) is different from the direction of the electric field vector directed toward the anode (anode electrode) 146. For this reason, the emitted electrons form a large electron distribution (beam spot) on the anode 146.

Here let us further consider the electric field for extracting electrons from the emitter electrode 145 (which will be called a "lateral electric field" herein for convenience' sake and the enhancement effect of the electric field by the emitter shape will be ignored herein) and the electric field directed toward the anode (which will be called a "vertical electric field"

herein).

In the configurations of Fig. 13 and Fig. 14, the foregoing "lateral electric field" can also be referred to as an "electric field in the substantially parallel direction to the surface of the substrate 131 (141)".
5 Particularly, in the configuration of Fig. 14, it can also be referred to as an "electric field in the facing direction of the gate 144 and the emitter 145".

In the configurations of Fig. 13 and Fig. 14, the
10 foregoing "vertical electric field" can also be referred to as an "electric field in the substantially normal direction to the surface of the substrate 131 (141)" or as an "electric field in the facing direction of the substrate 131 (141) and the anode 136 (146)".

15 As described previously, electrons emitted from the emitter 145 are first drawn by the lateral electric field to fly toward the gate 144 and thereafter they are moved up by the vertical electric field to reach the anode 146.

20 Important points at this time are a ratio of strengths of the lateral electric field and the vertical electric field and the relative position of electron emission point.

When the lateral electric field is stronger in
25 order of magnitude than the vertical electric field, most of the electrons emitted from the emitter fly in trajectories gradually bent by radial potentials formed

by the lateral electric field and directed toward the gate. Part of the electrons colliding with the gate are again emitted because of scattering, and thereafter are repeatedly scattered as spreading on the gate while
5 drawing trajectories similar to ellipses many times and as reducing the number of emitted electrons, before they are captured by the vertical electric field. When the scattered electrons then cross an equipotential line made by the gate potential (which is also called a
10 "stagnation point"), they are moved up by the vertical electric field for the first time.

When the lateral electric field and the vertical electric field are approximately equal in strength to each other, the extracted electrons also fly in
15 trajectories bent by the radial potentials, but the binding by the electric field becomes weaker, so that there appear trajectories of electrons captured by the vertical electric field without colliding with the gate
144.

20 It was verified that with the lateral electric field and vertical electric field approximately equal in strength to each other, as the position of the electron emission point from the emitter 145 was gradually lifted up from the plane to which the gate
25 144 belonged, toward the plane to which the anode 146 belonged (see Fig. 6), the emitted electrons could fly in trajectories captured by the vertical electric field

without colliding with the gate 144 at all.

Research was conducted about the electric field ratios and it was found from the research that, where d represented the spacing between the gate electrode 144 and the tip of the emitter electrode 145, V_1 the potential difference (the potential difference between the gate electrode and the emitter electrode) during driving of the device, H the distance between the positive electrode (anode) and the substrate (device), and V_2 (V_a) the potential difference between the positive electrode (anode) and the negative electrode (emitter electrode), the extracted electrons drew the trajectories colliding with the gate when the lateral electric field was 50 or more times stronger than the vertical electric field.

The inventor also discovered that there existed a height s causing no substantial scattering on the gate electrode 2 (which is defined by a distance between a plane including part of the surface of the gate electrode 2 and being substantially parallel to the surface of the substrate 1 and a plane including the surface of the electron-emitting member 4 and being substantially parallel to the surface of the substrate 1 (see Fig. 6)). This height s is dependent upon the ratio of the vertical electric field and the lateral electric field (strength of the vertical electric field/strength of the lateral electric field) and the

height becomes lower with decrease in the vertical-lateral electric field ratio and becomes higher with increase in the lateral electric field.

A practical fabrication range of the height s is
5 not less than 10 nm nor more than 10 μ m.

In the conventional configuration shown in Fig. 14, since the gate 144 and the emitter (142, 145) were formed at the same height on the same plane and since the lateral electric field was stronger by one or more
10 figures than the vertical electric field, there was the strong tendency that the number of extracted electrons into the vacuum decreased because of the collision with the gate.

Further, in the conventional configuration, since
15 the thickness and width of the gate electrode and the relative positions of the gate, emitter, and anode were determined for the purpose of enhancing the intensity of the lateral electric field, the electron distribution on the anode became expanded.

20 As described previously, in order to make small the distribution of electrons reaching the anode 146, it is necessary to consider 1) decreasing the driving voltage (V_f), 2) aligning the extraction directions of electrons, 3) trajectories of electrons, and, further,
25 in the case involving the scattering on the gate, 4) the scattering mechanisms of electrons (particularly, elastic scattering).

The electron-emitting devices using the fibrous carbons according to the present invention realize both the size reduction of the electron distribution on the anode electrode and improvement in the electron
5 emission efficiency (decrease of emitted electrons absorbed by the gate electrode).

Configurations of the electron-emitting devices according to the present invention will be described below in further detail with reference to the drawings.
10 Figs. 1A and 1B are schematic views showing an example of the electron-emitting device according to the present invention, wherein Fig. 1A is a plan view thereof and Fig. 1B a cross-sectional view along 1B-1B in Fig. 1A. Fig. 6 is a schematic cross-sectional view
15 showing a state of driving of the electron-emitting apparatus according to the present invention in which the anode electrode is placed above the electron-emitting device of the present invention.

In Figs. 1A and 1B and Fig. 6, numeral 1
20 designates an electrically insulating substrate, 2 an extraction electrode (also called "gate electrode" or "second electrode"), 3 a negative electrode (also called "first electrode" or "cathode electrode"), 4 fibrous carbons being an emitter material (also called
25 "electron-emitting material" or "electron-emitting member"), and 5 a first layer for selective growth of the fibrous carbons, which is an oxide of a material

selected from Ti, Zr, and Nb, described previously.
The fibrous carbons constituting the electron-emitting
material 4 are electrically connected to the electrode
3. Numeral 6 denotes a second layer.

5 In the present invention, the important structure
is that the negative electrode 3 and the extraction
electrode 2 are placed with a gap in between on the
surface of the substrate and a plurality of fibrous
carbons 4 are placed on a surface of the negative
10 electrode 3 facing the extraction electrode 2. In
other words, the plurality of fibrous carbons extending
in the facing direction of the negative electrode 3 and
the extraction electrode 2 are located on the negative
electrode 3 in the gap between the negative electrode 3
15 and the extraction electrode 2. This configuration
permits electrons to be emitted by a lower electric
field.

 Further, in the present invention, the important
structure is that, in order to prevent unnecessary
20 electrons from being emitted, the fibrous carbons are
not placed on the surfaces except for the surface
facing the extraction electrode 2. This structure can
restrain the expansion of the electron beam irradiating
the anode electrode.

25 In the example of Figs. 1A, 1B, the first layer 5
and the second layer 6 are provided for controlling the
region where the fibrous carbons are formed. Namely,

the first layer 5 is made of a material permitting the fibrous carbons 4 to grow thereon, while the second layer 6 is made of a material not permitting the fibrous carbons 4 to grow thereon, as compared with the first layer 5. The first layer and second layer described above are preferably electrically conductive. Particularly, the second layer is especially preferably electrically conductive, because it is exposed in vacuum. In the configuration as shown in Figs. 1A, 1B, unless the first layer 5 is electrically conductive, electrical connection cannot be established between the negative electrode 3 and the fibrous carbons; therefore, the first layer 5 is preferably selected from electroconductive materials.

The example with provision of the second layer 6 was described herein, but this layer does not always have to be provided. For example, it is also possible to construct an electron-emitting device of the present invention by making the negative electrode 3 of a material selected from Ti, Zr, and Nb and oxidizing only a surface thereof facing the extraction electrode 2 among its surfaces (i.e., by placing the first layer).

In the form shown in Figs. 1A, 1B, all the first layer 5 does not have to be made of an oxide, but it is also possible to make at least only the surface facing to the extraction electrode 2 among the surfaces of the

first layer 5, of an oxide. This structure makes the second layer not always necessary. Even if the first layer is thick, such structure can enhance the electrical connection between the negative electrode 3
5 and the fibrous carbons.

The electron-emitting device according to the present invention can also be constructed in such a way that the negative electrode 3 is made of a material selected from Ti, Zr, and Nb, the surface thereof
10 (including the surface facing the extraction electrode 2) is oxidized, and the surfaces other than the surface facing the extraction electrode 2 (i.e., the surface on which the fibrous carbons are laid) are coated with a layer (the second layer) made of a material permitting
15 no growth of fibrous carbons as compared with the oxide of the material selected from Ti, Zr, and Nb.

In the electron-emitting apparatus of the present invention, as shown in Figs. 1A, 1B and Fig. 6, the plane including the surface of the electron-emitting
20 member 4 and being substantially parallel to the surface of the substrate 1 is preferably more distant from the surface of the substrate than the plane including part of the surface of the gate electrode 2 and being substantially parallel to the surface of the
25 substrate 1. In other words, in the electron-emitting apparatus of the present invention, the plane including part of the surface of the electron-emitting member 4

and being substantially parallel to the surface of the substrate 1 is located between the anode electrode 61 and the plane including part of the surface of the extraction electrode 2 and being substantially parallel to the surface of the substrate. This structure can realize the reduction of electrons absorbed into the gate electrode and the reduction of the spot size of the electron beam impinging on the anode electrode.

Further, in the electron-emitting device of the present invention, the electron-emitting member 4 is located at the height s (defined as the distance between the plane including part of the surface of the gate electrode 2 and being substantially parallel to the surface of the substrate 1 and the plane including the surface of the electron-emitting member 4 and being substantially parallel to the surface of the substrate 1) at which no substantial scattering of electrons occurs on the gate electrode 2.

The above height s is dependent upon the ratio of the vertical electric field and the lateral electric field (intensity of the vertical electric field/intensity of the lateral electric field), and the height needs to be decreased with decrease in the ratio of the vertical electric field and the lateral electric field and to be increased with increase in the intensity of the lateral electric field; the practical range of the height s is not less than 10 nm nor more

than 10 μm .

This structure can be readily realized, for example, by making the thickness of the negative electrode 3 larger than the thickness of the extraction electrode 2. Alternatively, it can also be realized by forming the negative electrode 3 and the extraction electrode 2 in equivalent thickness and placing the first layer 5 on the negative electrode 3.

In the electron-emitting apparatus of the present invention, where, in the structure shown in Fig. 6, d represents the distance of the gap between the negative electrode 3 and the gate electrode 2, V_f the potential difference during driving of the electron-emitting device (the voltage between the negative electrode 3 and the gate electrode 2), H the distance between the anode electrode 61 and the surface of the substrate 1 on which the device is placed, and V_a the potential difference between the anode electrode 61 and the negative electrode 3, the electric field (lateral electric field) during the driving: $E_1 = V_f/d$ is set to be not less than 1 times nor more than 50 times stronger than the electric field (vertical electric field) between the anode 61 and the cathode 3: $E_2 = V_a/H$.

This setting can almost nullify the ratio of electrons colliding with the gate electrode 2 to electrons emitted from the negative electrode 3. As a

result, there are provided the electron-emitting device and the electron-emitting apparatus with the extremely small spread of the emitted electron beam and with high electron emission efficiency.

5 The "lateral electric field" stated in the present invention can be referred to as the "electric field in the direction substantially parallel to the surface of the substrate 1". In another sense, it can also be referred to as the "electric field in the facing
10 direction of the gate 2 and the cathode electrode 3". The "vertical electric field" stated in the present invention can be referred to as the "electric field in the direction substantially normal to the surface of the substrate 1" or the "electric field in the facing
15 direction of the substrate 1 and the anode electrode 61".

 The electrically insulating substrate 1 can be either of laminations in which SiO_2 is laid by sputtering or the like on a well-cleaned surface of
20 either of silica glass, glasses partly replaced with K or the like while reducing the impurity content of Na and others, soda lime glass, silicon substrates, etc. insulating substrates of ceramics such as alumina or the like, and so on.

25 The extraction electrode 2 and the negative electrode 3 are electrically conductive and are made by either of the ordinary vacuum film-forming technologies

such as vacuum evaporation, sputtering, and the like, or the photolithography technology.

The materials of the extraction electrode 2 and the negative electrode 3 are adequately selected, for example, from carbon, metals, nitrides of metals, carbides of metals, borides of metals, semiconductors, and metal semiconductors compounds.

The thicknesses of the extraction electrode 2 and the negative electrode 3 are set in the range of several ten nm to several ten μm . Preferably, they are desirably made of either of heat resistant materials such as carbon, metals, nitrides of metals, and carbides of metals.

When there is a worry that a potential drop or the like can occur because of the small thickness of the electrodes or when such devices are used in a matrix array, a low-resistant metal material for wiring is sometimes used in portions not associated with the emission of electrons as occasion may demand.

In comparison of electric field intensities between the electron emission field of the cathode material used (the lateral electric field) and the vertical electric field necessary for the formation of image, the gap between the extraction electrode 2 and the negative electrode 3 (the width of the gap) and the driving voltage are preferably designed so that the electron emission field becomes approximately 1 times

to 50 times stronger than the vertical electric field.

In the present invention, the emitter (electron-emitting member) 4 is comprised of fibrous carbons.

The fibrous carbons are preferably those obtained
5 by forming nuclei with use of a catalyst and growing
the fibrous carbons from the nuclei by thermal
decomposition.

According to the present invention, the "fibrous
carbons" can also be said as "columnar substances
10 comprising carbon as a main component" or "linear
substances comprising carbon as a main component". The
"fibrous carbons" can also be mentioned as "fibers
comprising carbon as a main component". More
specifically, the "fibrous carbons" in the present
15 invention embrace carbon nanotubes, graphite
nanofibers, and amorphous carbon fibers. Among these,
the graphite nanofibers are most preferable for the
electron-emitting member 4.

The gap between the extraction electrode 2 and the
20 negative electrode 3 and the driving voltage are
preferably designed so that, in comparison of electric
field intensities between the electron emission field
of the electron-emitting member (the lateral electric
field) and the vertical electric field necessary for
25 the formation of image, the electron emission field
becomes approximately 1 times to 50 times stronger than
the vertical electric field, as described previously.

When a light emitting member such as a phosphor or the like is placed on the positive electrode (anode electrode), the necessary vertical field is preferably in the range of not less than 10^{-1} V/ μ m nor more than 10 V/ μ m. For example, where the gap between the positive electrode (anode electrode) and the negative electrode is 2 mm and 10 kV is placed in the gap, the vertical electric field at this time is 5 V/ μ m. In this case, the emitter material (electron-emitting member) 4 to be used is one having the electron emission field larger than 5 V/ μ m, and the spacing and driving voltage can be determined so as to realize the selected electron emission field.

The aforementioned fibrous carbons are preferably applicable as materials having the threshold electric field of several V/ μ m as described above.

Fig. 11 and Fig. 12 show examples of forms of the fibrous carbons suitably applicable to the present invention. In each figure the left view schematically shows a form observed at the optical microscope level (approximately 1000 \times), the center view a form observed at the scanning electron microscope (SEM) level (approximately 30,000 \times), and the right view a form of carbon observed at the transmission electron microscope (TEM) level (approximately 1 million \times).

As shown in Fig. 11, the form of cylindrical shape of graphen is called a carbon nanotube (a multiple

structure of cylinders is called a multiwall nanotube), and the threshold thereof becomes the lowest, particularly, in the structure in which the tube is open at the tip.

5 As another example, fibrous carbons may be produced at relatively low temperatures are shown in Fig. 12. A fibrous carbon of this form is comprised of a lamination of graphens (which is thus sometimes called "graphite nanofiber" and the rate of amorphous
10 structure of which increases depending upon the temperature). More specifically, the graphite nanofiber indicates a fibrous substance in which graphens are layered (laminated) in the longitudinal direction thereof (in the axis direction of the fiber).
15 In other words, as shown in Fig. 12, it is a fibrous substance in which a plurality of graphens are arranged and layered (laminated) so as not to be parallel to the axis of fiber.

 On the other hand, a carbon nanotube is a fibrous
20 substance in which graphens are arranged (in cylindrical shape) around the longitudinal direction (the axis direction of fiber). In other words, it is a fibrous substance in which graphens are arranged substantially in parallel to the axis of the fiber.

25 A single surface of graphite will be called a "graphen" or "graphen sheet". More specifically, graphite is a lamination in which carbon planes, each

of which is a spread of regular hexagons consisting of covalent bonds of carbon atoms in sp^2 hybrid, are layered at intervals of distance of 3.354 Å. Each of the carbon planes is called a "graphen" or "graphen sheet".

All the fibrous carbons have the threshold for the emission of electron in the range of approximately 1 to 10 V/μm and are very suitable for the emitter (electron-emitting member) 4 of the present invention.

Particularly, the electron-emitting devices using the graphite nanofibers can be those capable of emitting electrons at a low electric field and yielding a large emission current, capable of being produced readily, and exhibiting stable electron emission characteristics, without having to be limited to the device structure of the present invention shown in Figs. 1A, 1B and others. For example, an electron-emitting device can be constructed by making the emitter of graphite nanofibers and preparing the electrode for control of electron emission from this emitter, and a light emitting apparatus such as a lamp or the like can also be formed by using a light emitting member which emits light under irradiation of electrons emitted from the graphite nanofibers. Further, it is also possible to construct an image display apparatus such as a display or the like by arraying a plurality of such electron-emitting devices

using the graphite nanofibers and preparing an anode electrode having a light emitting member such as a phosphor or the like. In the electron-emitting apparatus, the light emitting apparatus, and the image display apparatus using the graphite nanofibers, stable electron emission can be implemented without need for maintaining the interior in such an ultrahigh vacuum as required in the conventional electron-emitting devices, and a high electron emission amount can be ensured at a low electric field; therefore, the apparatus can be fabricated extremely simply with high reliability.

The aforementioned fibrous carbons can be made by decomposing a hydrocarbon gas under use of a catalyst (a material for promoting deposition of carbon). The carbon nanotubes and graphite nanofibers differ depending upon the type of the catalyst and the temperature of decomposition.

The catalyst materials, such as Fe, Co, Pd, Ni and alloy of material selected from those materials can be used as the nuclei for formation of the fibrous carbons.

Particularly, in the case of Pd, the graphite nanofibers can be produced at low temperatures (temperatures of not less than 400°C). On the other hand, when the catalyst is Fe or Co, the temperature for production of carbon nanotubes needs to be not less than 800°C. Since the production of the graphite

nanofiber material using Pd can be implemented at low temperatures, it is also preferable in terms of influence on the other members and the production cost.

Further, in the case of the Pd catalyst, using the
5 property that the oxide thereof is readily reduced by hydrogen at low temperatures (room temperature), it is feasible to use palladium oxide as a nucleation material.

By employing the hydrogen reduction treatment of
10 palladium oxide, it became feasible to form the initial aggregated nuclei at relatively low temperatures (200°C or less) without use of thermal aggregation of metal thin film or production and evaporation of ultrafine particles accompanied by a danger of explosion which
15 are conventionally used as ordinary nucleation techniques.

The foregoing hydrocarbon gas can be, for example, either of hydrocarbon gases such as ethylene, methane, propane, propylene, and so on, or vapors of organic
20 solvents such as ethanol, acetone, and so on.

The raw materials for the fibrous carbons can also be such raw materials as CO, CO₂, and the like, in addition to the foregoing hydrocarbon gases.

The material of the layer 5 allowing the growth of
25 fibrous carbons 4 is a mixture of Ti and an oxide thereof resulting from partial oxidation of Ti, or an oxide semiconductor of Ti; or a mixture of Zr and an

oxide thereof resulting from partial oxidation of Zr,
or an oxide semiconductor of Zr; or a mixture of Nb and
an oxide thereof resulting from partial oxidation of
Nb, or an oxide semiconductor of Nb, as described
5 previously. The foregoing oxide of Ti, oxide of Zr, or
oxide of Nb is placed at least on the surface for the
fibrous carbons 4 to be placed, among the surfaces of
the layer 5.

These oxides of Ti, Zr, and Nb are
10 stoichiometrically insulators, but weakly oxidized
substances thereof or suboxides thereof possess a
number of defects inside and thus form semiconductors
of the oxygen deficient type or the like.

The layer 5 and the catalyst particles placed on
15 the layer 5 can be produced, for example, by a method
of baking Pd on the layer of Ti, Zr, or Nb at the
temperature of about 300°C for about several ten
minutes to form palladium oxide and simultaneously
oxidizing the layer of Ti, Zr, or Nb as well. The
20 baking temperature and time of this level, however, do
not oxidize the entire layer, though depending upon the
thickness of the layer of Ti, Zr, or Nb, but oxidize
only the surface. Since such oxide has the
semiconductorlike nature as described above, the layer
25 5 thus formed results in possessing electrical
conductivity.

The second layer 6 is comprised of a material on

which no substantial growth of fibrous carbon occurs,
as compared with the first layer 5, even if the
catalyst particles are placed thereon. Such materials
can be aforementioned Ta, Cr, Au, Ag, Pt, or materials
5 of the same kinds as the catalyst materials. Then the
region except for the side face of the first layer 5 on
the extraction electrode 2 side is covered by the
second layer 6.

As a result, only the side wall of the layer 5 on
10 the extraction electrode 2 side is exposed, and thus
the fibrous carbons 4 grow only on the side wall on the
extraction electrode 2 side in the subsequent step of
growth of fibrous carbons.

If the device should not have the conductive layer
15 6 on which the fibrous carbons do not grow through the
fine catalyst particles, the fibrous carbons would grow
over the entire surface of the conductive layer 5 on
which the fibrous carbons can grow through the fine
catalyst particles. In this case, the fibrous carbons
20 apart from the gate electrode 2 would be involved in
emission of electrons, though it is a little, and such
electrons could disturb the beam profile and
uniformity.

In contrast with it, the electron-emitting device
25 according to the present embodiment can be constructed
in the configuration wherein there exists no fibrous
carbons on the side walls except for the side wall on

the extraction electrode 2 side, and it is thus feasible to prevent the disturbance of the beam profile and uniformity.

5 The position of the electron emission point in the emitter region and the operation thereof will be described below referring to Fig. 6 and Fig. 7.

10 The instant device having the gap length d of several μm was placed in a vacuum chamber 60, as shown in Fig. 6, and then the interior thereof was evacuated well down to about 10^{-4} Pa by an vacuum pump 65. While the positive electrode (hereinafter referred to as an anode) 61 was set at the position of the height H of several millimeters from the substrate 1, a high voltage V_a of several kV was applied from a
15 voltage source.

A fluorescent member 62 with an electroconductive film coating thereon was placed on the anode 61.

20 A pulse voltage of about several ten V was applied as the driving voltage V_f between the electrode 2 and the electrode 3 to measure the device current I_f and electron emission current I_e . Naturally, the driving voltage V_f was applied so that the potential at the gate electrode 2 was higher than that at the negative electrode 3.

25 At this time, equipotential lines 63 are formed as shown, and the electric field is most concentrated at the part indicated by point 64 closest to the anode 61

among the fibrous carbons 4 of the electron-emitting material and inside the gap.

It is speculated that electrons are emitted from the site where the electric field is most concentrated
5 in the electron-emitting material located in the vicinity of this field concentrating point 64.

The I_e characteristic of the device was that shown in Fig. 7. Namely, I_e demonstrated a sudden rise from about half of the applied voltage, and I_f , not shown,
10 was similar to the characteristic of I_e but considerably smaller than I_e .

Based on this principle, an electron source and an image-forming apparatus comprised of a plurality of electron-emitting devices according to the embodiment
15 of the present invention will be described hereinafter with reference to Fig. 8 to Fig. 10. Fig. 8 is a schematic plan view of electron source according to an embodiment of the present invention, Fig. 9 a perspective view of an image-forming apparatus, partly
20 broken, according to an embodiment of the present invention, and Fig. 10 a block diagram of an image-forming apparatus according to an embodiment of the present invention.

In Fig. 8, numeral 81 denotes an electron source substrate, 82 X-directional wires, and 83 Y-directional
25 wires. Numeral 84 denotes electron-emitting devices according to the embodiment of the present invention,

and 85 interconnections.

In this configuration the placement of plural electron-emitting devices 84 is accompanied by increase in the capacitance of the devices, and there arises a
5 problem that in the matrix wiring shown in Fig. 8, waves become dull because of the capacitance component, so as to fail to attain expected gradation even with application of short pulses according to pulse width modulation.

10 In order to avoid it, it is preferable to employ a structure for reducing the increase of the capacitance component except for that in the electron emission section, for example, by placing an interlayer electric film (rear plate 91) right next to the electron
15 emission section, as shown in Fig. 9.

In Fig. 8, the m X-directional wires 82 consist of DX_1, DX_2, \dots, DX_m and are made of an aluminum based wiring material in the thickness of about $1\ \mu\text{m}$ and in the width of $300\ \mu\text{m}$ by evaporation. However, the
20 material, thickness, and width of the wires are properly designed according to respective cases.

On the other hand, the Y-directional wires 83 consist of n wires of DY_1, DY_2, \dots, DY_n $0.5\ \mu\text{m}$ thick and $100\ \mu\text{m}$ wide and are made in similar fashion to the X-
25 directional wires 82.

An interlayer dielectric film not shown is disposed between these m X-directional wires 82 and n

Y-directional wires 83, so as to electrically isolate them from each other (where m and n are positive integers).

5 The unrepresented interlayer dielectric film is made of SiO_2 in the thickness of about 0.8 μm by sputtering or the like.

10 The interlayer dielectric film is formed in the desired shape over the entire surface or in part of the substrate 81 after formation of the X-directional wires 82, and the thickness of the interlayer dielectric film is determined so that the device capacitance per device is not more than 1 pF and the device withstand voltage 30 V in the present embodiment, particularly, in order to resist the potential difference at intersections
15 between the X-directional wires 82 and the Y-directional wires 83. The X-directional wires 82 and Y-directional wires 83 are drawn out as respective external terminals.

20 Pairs of electrodes (not shown) making up the electron-emitting devices 84 according to the embodiment of the present invention are electrically connected by the m X-directional wires 82, n Y-directional wires 83, and interconnections 85 of an electroconductive metal or the like.

25 Connected to the X-directional wires 82 is an unrepresented scanning signal applying means for applying a scanning signal for selection of a row of

electron-emitting devices 84 according to the embodiment of the present invention, arrayed in the X-direction.

5 Connected to the Y-directional wires 83 on the other hand is an unrepresented modulation signal generating means for modulating each column of electron-emitting devices 84 according to the embodiment of the present invention, arrayed in the Y-direction, according to an input signal.

10 The driving voltage applied to each electron-emitting device is supplied as a difference signal between a scanning signal and a modulation signal applied to the device. In the embodiment of the present invention, electrical connection is established
15 so that the Y-directional wires are at a higher potential while the X-directional wires at a lower potential. This connection yields the beam converging effect, which is a feature of the embodiment of the present invention.

20 In the above configuration, the individual devices can be selected to be driven independently by use of the simple matrix wiring.

 An image-forming apparatus constructed by use of the electron source of this simple matrix configuration
25 will be described referring to Fig. 9. Fig. 9 shows a display panel of the image-forming apparatus wherein soda lime glass is used as a material of a glass

substrate.

In Fig. 9, numeral 81 designates an electron source substrate loaded with a plurality of electron-emitting devices, 91 a rear plate to which the electron source substrate 81 is fixed, and 96 a face plate wherein a florescent film 94, a metal back 95, etc. are formed on an internal surface of glass substrate 93. Numeral 92 denotes a support frame, and the rear plate 91 and face plate 96 are coupled to this support frame 92 with frit glass or the like. Numeral 97 represents an envelope which is sealed by baking it in the temperature range of 450°C in vacuum for ten minutes.

Numeral 84 indicates the electron emission regions and numerals 82 and 83 denote the X-directional wires and Y-directional wires, respectively, which are connected to the pairs of device electrodes of the electron-emitting devices according to the embodiment of the present invention.

The envelope 97 is composed of the face plate 96, the support frame 92, and the rear plate 91, as described above. When an unrepresented support called a spacer is interposed between the face plate 96 and the rear plate 91, the envelope 97 can be constructed with sufficient strength against the atmospheric pressure.

The metal back 95 can be made in such a way that after production of the fluorescent film, the internal

surface of the fluorescent film is subjected to a smoothing process (normally called "filming") and thereafter Al is deposited thereon by vacuum evaporation or the like.

5 The face plate 96 is further provided with a transparent electrode (not shown) on the outer surface side of the fluorescent film 94, in order to further enhance the electrical conductivity of the fluorescent film 94.

10 During the aforementioned sealing operation, in the color display case, correspondence has to be made between respective color phosphors and electron-emitting devices and thus sufficient alignment is essential.

15 Next, a scanning circuit 102 shown in Fig. 10 will be described below. This circuit is provided with M switching devices inside (schematically indicated by S1 to Sm in the figure). Each switching device selects either an output voltage of a dc voltage source Vx or 0
20 V (the ground level) to be electrically connected to a terminal Dx1 to Dxm of display panel 101.

Each switching device of S1 to Sm operates based on a control signal Tscan from a control circuit 103 and can be constructed, for example, of a combination
25 of switching devices such as FETs.

The dc voltage source Vx is set to output such a constant voltage that the driving voltage applied to

non-scanned devices is not more than the electron emission threshold voltage, based on the characteristics of the electron-emitting devices (electron emission threshold voltage) according to the embodiment of the invention, in the case of the present example.

The control circuit 103 has the function of matching operations of respective portions so as to implement appropriate display based on image signals supplied from the outside. The control circuit 103 generates control signals of Tscan, Tsft, and Tmry to the respective portions, based on a synchronizing signal Tsync supplied from a synchronizing signal separating circuit 106.

The synchronizing circuit 106 is a circuit for separating the synchronizing signal component and luminance signal component from a TV signal of the NTSC system supplied from the outside, and can be composed of an ordinary frequency separating (filter) circuit or the like.

Although the synchronizing signal separated by the synchronizing signal separating circuit 106 consists of a vertical synchronizing signal and a horizontal synchronizing signal, it is illustrated as a Tsync signal herein for convenience' sake of description. The luminance signal component of an image separated from the aforementioned TV signal is indicated as a

DATA signal for convenience' sake. This DATA signal is entered into a shift register 104.

The shift register 104 performs serial-parallel conversion for each line of an image with reception of DATA signals serially supplied in time sequence and
5 operates based on the control signal Tsft sent from the control circuit 103. Namely, the control signal Tsft can also be called as a shift clock for the shift register 104.

10 Data of one line of an image after the serial-parallel conversion (corresponding to driving data for N devices out of the electron-emitting devices) is outputted as N parallel signals of Id1 to Idn from the shift register 104.

15 A line memory 105 is a storage device for storing the data of one line of an image for a required time and is configured to store the contents of Id1 to Idn properly according to the control signal Tmry sent from the control circuit 103. The stored contents are
20 outputted as I'd1 to I'dn to enter a modulation signal generator 107.

The modulation signal generator 107 is a signal source for appropriately modulating each of the electron-emitting devices of the present embodiment
25 according to each of the image data I'd1 to I'dn, and output signals therefrom are applied through terminals Doy1 to DoyN to the electron-emitting devices of the

present embodiment in the display panel 101.

As described previously, the electron-emitting devices according to the embodiment of the present invention have the following basic characteristics
5 concerning the emission current I_e .

Namely, there is the definite threshold voltage V_{th} for the emission of electrons and electrons are emitted only when a voltage not less than V_{th} is applied.

10 At voltages not less than the electron emission threshold, the emission current also varies according to variation in the applied voltage to the devices. For this reason, when the pulse voltage is applied to the instant devices, for example, electrons are not
15 emitted with application of a voltage not more than the electron emission threshold but an electron beam is outputted with application of a voltage not less than the electron emission threshold.

On that occasion, the intensity of the output
20 electron beam can be controlled by varying the peak height V_m of pulses. It is also possible to control the total charge amount of the output electron beam by changing the width P_w of pulses.

Accordingly, either of the voltage modulation
25 method, the pulse width modulation method, etc. can be employed as a method of modulating the electron-emitting devices according to input signals. For

carrying out the voltage modulation method, the modulation signal generator 107 can be a circuit of the voltage modulation method configured to generate voltage pulses of a fixed length and modulate peak heights of pulses adequately according to input data.

For carrying out the pulse width modulation method, the modulation signal generator 107 can be a circuit of the pulse width modulation method configured to generate voltage pulses of a fixed peak height and modulate widths of the voltage pulses adequately according to input data.

The shift register 104 and the line memory 105 are of the digital signal type.

The modulation signal generator 107 is, for example, a D/A converting circuit and an amplifying circuit or the like is added thereto as occasion demands. In the case of the pulse width modulation method, the modulation signal generator 107 is, for example, a circuit consisting of a combination of a fast oscillator and a counting device (counter) for counting the number of waves from the oscillator with a comparing device (comparator) for comparing an output value of the counter with an output value of the memory.

The configuration of the image-forming apparatus stated herein is just an example of the image-forming apparatus to which the present invention is applicable,

and a variety of modifications can be made based on the technical concept of the present invention. The input signals were of the NTSC system, but the input signals are not limited to this system; for example, it is also
5 possible to employ the PAL system, SECAM system, etc., and systems of TV signals consisting of a larger number of scanning lines than them (for example, high-definition TV systems including the MUSE system).

Examples

10 More specific examples based on the above embodiments will be described below in detail.
(Example 1)

In the present example, the basic configuration is comprised of the configuration shown in Figs. 1A and 1B
15 as described in the above-stated embodiment.

The steps for fabrication of the electron-emitting device according to the present example will be described below in detail with reference to Figs. 5A to 5E.

20 (Step 1)

After a silica substrate used as the substrate 1 was cleaned well, a Ti layer 5 nm thick and a Pt layer 500 nm thick, not shown, were first consecutively evaporated over the entire surface of the substrate by
25 sputtering, in order to form the extraction electrode 2 and the negative electrode 3.

Then a resist pattern was formed with an

unrepresented positive photoresist (AZ1500 available from Clariant) by the photolithography process.

Using the patterned photoresist as a mask, the Pt layer and Ti layer were then subjected to dry etching
5 with Ar gas to pattern the extraction electrode 2 and the negative electrode 3 with the electrode gap (the width of gap) of 5 μm (a state shown in Fig. 5A).

The patterning of a thin film or a resist by the photolithography process, film formation, lift-off,
10 etching, etc. will be referred to hereinafter simply as patterning.

(Step 2)

Then an unrepresented Cr layer was deposited in the thickness of about 100 nm over the entire surface
15 of the substrate by electron beam evaporation and the positive photoresist (AZ1500 available from Clariant) was patterned thereon.

Using the patterned photoresist as a mask, a region (100 μm \times 80 μm) to cover the conductive layer
20 for growth of fibrous carbons through the catalyst particles was then formed on the negative electrode 3 and the Cr layer in the opening portion was removed with a cerium nitrate based etchant.

Then a Ti layer for growth of fibrous carbons
25 through the catalyst particles was evaporated in the thickness of 50 nm by sputtering.

Then the unnecessary Ti layer and resist were

removed simultaneously (lift-off method), thereby forming the Ti conductive layer 5 (a state shown in Fig. 5B).

(Step 3)

5 By the patterning similar to step 2, the Ti conductive layer 5 was covered by the Ta conductive layer 6 ($140\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$) not permitting the growth of fibrous carbons through the catalyst particles, so as to expose only the side wall of the Ti conductive layer
10 5 on the extraction electrode side (a state shown in Fig. 5C).

(Step 4)

 In the subsequent step, an unrepresented Cr layer of about 100 nm was patterned so as to expose only side
15 walls of the Pt/Ti layers (equivalent of the negative electrode 3), the Ti conductive layer 5, and the Ta conductive layer 6 on the extraction electrode side.

 Then a complex solution obtained by adding isopropyl alcohol or the like to a Pd complex was
20 applied onto the entire surface of the substrate by spin coating.

 After the application, a heat treatment was carried out at 300°C in the atmosphere to form a palladium oxide layer in the thickness of about 10 nm
25 over the entire surface. Thereafter, Cr was removed with the cerium nitrate based etchant to lift off the unnecessary palladium oxide thereby, thus forming the

patterned palladium oxide layer.

After evacuation of atmosphere, the substrate was heated to 200°C to carry out a heat treatment in a 2% hydrogen stream diluted with nitrogen. At this stage
5 the catalyst particles 52 were formed in particle diameters of about 3 to 10 nm on the wall surfaces in the surface of device. The density of the particles at this time was estimated as about 10^{11} to 10^{12} particles/cm² (a state shown in Fig. 5D).

10 (Step 5)

In the subsequent step, a heat treatment was conducted at 500°C in a 0.1% ethylene stream diluted with nitrogen for ten minutes. The resultant was observed with the scanning electron microscope and it
15 was verified therefrom that a number of fibrous carbons 4 extending in fibrous shape as bent were formed in the diameters of about 10 nm to 25 nm only on the wall surface of the Ti conductive layer 5 permitting the growth of fibrous carbons through the catalyst
20 particles among the catalyst particles on the wall surfaces.

The thickness of the fibrous carbons 4 at this time was about 500 nm. No fibrous carbon 4 was recognized on the wall surfaces of the Pt layer
25 (negative electrode 3) and the Ta conductive layer 6 not permitting the growth of fibrous carbons through the catalyst particles (a state shown in Fig. 5E).

The electron-emitting device fabricated as described above was set in the vacuum chamber 60 as shown in Fig. 6 and the interior thereof was evacuated well down to the vacuum of 2×10^{-5} Pa by the evacuator
5 65.

Then the anode voltage of $V_a = 10$ kV was applied to the positive electrode (anode) 61 H = 2 mm apart from the device, as shown in Fig. 6. At this time, while the pulse voltage consisting of the driving
10 voltage (the voltage placed between the electrodes 2, 3) $V_f = 20$ V was applied to the device, the flowing device current I_f and electron emission current I_e were measured.

The I_f and I_e characteristics of the device were
15 those shown in Fig. 7. Namely, I_e demonstrated a sudden increase from about half of the applied voltage and the electron emission current I_e of about 1 μ A was measured at V_f of 15 V. On the other hand, I_f was similar to the characteristic of I_e but values thereof
20 were a figure or more smaller than those of I_e .

The resultant beam was approximately of a rectangular shape slender in the Y-direction and short in the X-direction.

Beam widths were measured under such conditions
25 that the voltage (V_f) placed between the negative electrode 3 and the gate electrode 2 was fixed at 15 V, the anode distance was fixed at H of 2 mm, the anode

voltage was either of 5 kV and 10 kV, and the gap (width of gap) was either of 1 μm and 5 μm , and the results are presented in Table 1 below.

TABLE 1

	Va = 5 kV		Va = 10 kV	
Gap : 1 μm	X-direction	60 μm	X-direction	30 μm
	Y-direction	170 μm	Y-direction	150 μm
Gap : 5 μm	X-direction	93 μm	X-direction	72 μm
	Y-direction	170 μm	Y-direction	150 μm

It was feasible to change the electric field necessary for the driving, by varying the growth conditions. Particularly, an average particle size of Pd particles obtained by the reduction treatment of palladium oxide is associated with the diameters of fibers formed by the growth thereafter.

The mean particle size of Pd particles was able to be controlled by the Pd concentration of the coated Pd complex and the rotational speed of the spin coating.

The carbon fibers of this device were observed with the transmission electron microscope and they were of the layered structure of graphens as shown on the right side of Fig. 12. The layer intervals of the graphens (in the direction of C-axis) were unclear at the temperature as low as about 500°C, and were 0.4 nm. As the temperature increased, the grating intervals became clearer, and at 700°C the intervals were 0.34 nm, which was close to 0.335 nm of graphite.

By employing the configuration of the electron-

emitting device according to the present example, as described above, the electron-emitting device was realized with the properties of the reduced capacitance and driving voltage, the high efficiency, and the small
5 beam size.

(Example 2)

The electron-emitting device according to Example 2 will be described below with reference to Figs. 2A and 2B. Figs. 2A and 2B are schematic views of the
10 electron-emitting device according to Example 2 of the present invention, wherein Fig. 2A is a plan view thereof and Fig. 2B a cross-sectional view along 2B-2B in Fig. 2A.

The electron-emitting device in the present
15 example was fabricated in the same manner as in Example 1 in the structure and others except that the thickness of the extraction electrode 2 in Example 1 was changed to 200 nm, and I_f and I_e were measured therewith.

In the structure of the instant device, the
20 thickness of the negative electrode 3 was larger than the thickness of the extraction electrode 2 whereby the electron emission position was able to be set surely at a higher position (on the anode side) from the extraction electrode 2.

25 This configuration decreased the number of electrons flying in the trajectories colliding with the gate, so as to be able to prevent the phenomena of

decrease of efficiency and increase of the beam size.

As a consequence, in the structure of the present device, the electron emission current I_e of about 1 μA was also measured at V_f of 20 V. On the other hand, I_f was similar to the characteristic of I_e but values thereof were two figures smaller than those of I_e . The beam sizes at this time were also approximately the same as in Table 1.

By employing the configuration of the electron-emitting device according to the present example, as described above, the electron-emitting device was realized with the properties of the reduced capacitance and driving voltage, the high efficiency, and the small beam size.

(Example 3)

The electron-emitting device according to Example 3 will be described with reference to Figs. 3A and 3B. Figs. 3A and 3B are schematic views of the electron-emitting device according to Example 3 of the present invention, wherein Fig. 3A is a plan view thereof and Fig. 3B a cross-sectional view along 3B-3B in Fig. 3A.

In the present example, the conductive layer 5 was formed up to an almost middle point of the gap across the gap from on the surface of the negative electrode 3 to on the surface of the substrate in step 2 in Example 1, whereby the gap distance was made to about half.

Since in the present device the gap distance was

smaller than in Example 1, the electric field was about two times stronger than in Example 1. This permitted the voltage for the driving to be reduced to about 8 V. Since the conductive layer 5 was used as an electrical
5 connection layer for the fibrous carbons 4, it became feasible to emit electrons stably from the fibrous carbons 4 in the gap.

By employing the configuration of the electron-emitting device according to the present example, as
10 described above, the electron-emitting device was realized with the properties of the reduced capacitance and driving voltage, the high efficiency, and the small beam size.

(Example 4)

15 The electron-emitting device according to Example 4 will be described with reference to Figs. 4A and 4B. Figs. 4A and 4B are schematic views of the electron-emitting device according to Example 4 of the present invention, wherein Fig. 4A is a plan view thereof and
20 Fig. 4B a cross-sectional view along 4B-4B in Fig. 4A.

The present example is different as follows in step 1 and step 2 described in foregoing Example 1, and the other steps of the present example are the same as in Example 1.

25 (Step 1)

After the silica substrate used as the substrate 1 was cleaned well, consecutive evaporation by sputtering

was conducted to form a Ti layer 5 nm thick and a Pt layer 500 nm thick as the cathode (emitter) electrode 3 and a Ti layer 100 nm thick as the conductive layer 5 permitting the growth of fibrous carbons.

5 Then a resist pattern was formed with the positive photoresist (AZ1500 available from Clariant) by the photolithography process.

 Using the patterned photoresist as a mask, the Ti conductive layer 5 was then etched by dry etching with
10 CF₄, and thereafter the Pt and Ti layers were etched by dry etching with Ar, thereby forming the negative electrode 3.

 Using the negative electrode 3 as a mask, the silica substrate was etched to the depth of about 500
15 nm with mixed acids consisting of hydrofluoric acid and ammonium fluoride.

 Subsequently, a Ti layer 5 nm thick and a Pt layer 30 nm thick were again consecutively evaporated as the extraction electrode 2 by sputtering. The photoresist
20 on the negative electrode 3 was removed and thereafter a resist pattern was again formed for formation of the gate electrode shape with the positive photoresist (AZ1500 available from Clariant).

 Using the patterned photoresist as a mask, the Pt
25 layer and the Ti layer were then etched by dry etching with Ar to form the extraction electrode 2 in such structure that a step difference between steps acted as

a gap.

Then a resist pattern was formed on the cathode and fine particles of Ni were formed in the thickness of about 5 nm by resistance heating evaporation with good straight-ahead nature. After that, an oxidation treatment was carried out at 350°C for 30 minutes. The steps after this step were the same as those in Example 1.

The configuration of this device permitted formation of a finer gap and made it feasible to emit electrons from about 6 V.

Since the height of the electron-emitting material (film thickness) was large, electrons were not emitted only from the upper part of the film but were also emitted from the middle point, so as to be able to prevent the decrease of efficiency and the increase of the beam size due to the collision of electrons with the gate electrode.

(Example 5)

An image-forming apparatus comprised of a plurality of electron-emitting devices according to the above examples will be described.

The electron-emitting devices of Example 1 were arrayed in a matrix pattern as shown in Fig. 8, thus completing the electron source substrate 81.

Using this electron source substrate 81, the positive electrode (anode) substrate 96 having the

fluorescent member 94 was placed at the distance of 2 mm above the electron-emitting devices 84, thus fabricating the image-forming apparatus shown in Fig. 9.

5 When the apparatus was driven by the pulse voltage of $V_f = 20$ V and V_a (voltage applied to the anode) = 10 kV, the properties similar to those in Example 1 were also yielded in the image-forming apparatus.

10 According to the present invention, as described above, the fibrous carbons are grown only on the side wall surface of the conductive layer on the extraction electrode side, whereby it is feasible to decrease electrons emitted from the other surfaces than the conductive layer, to enhance the electron emission efficiency, and to improve convergence of trajectories
15 of emitted electrons.

 When the electron-emitting devices superior in the electron emission efficiency and in the convergence of electron trajectories as described are applied to the
20 electron source, the electron source can be realized with high quality. When this electron source is applied to the image-forming apparatus, the image-forming apparatus can implement formation of higher definition images.

WHAT IS CLAIMED IS:

1. An electron-emitting device comprising:

(A) an extraction electrode and a negative
electrode formed in opposition to each other with a gap
5 between said extraction electrode and said negative
electrode on an electrically insulating substrate;

(B) a first layer formed on said negative
electrode and having an oxide of Ti, an oxide of Zr, or
an oxide of Nb on a surface thereof; and

10 (C) a fibrous carbon grown through a catalyst
particle disposed on a side wall surface of said first
layer on the extraction electrode side.

2. The electron-emitting device according to

15 Claim 1, wherein only the side wall surface of said
first layer on the extraction electrode side is exposed
and the other surfaces thereof are covered with a
material on which a fibrous carbon does not grow as
compared with said first layer.

20 3. The electron-emitting device according to

Claim 2, wherein said material on which a fibrous
carbon does not grow as compared with said first layer,
is at least either one of Ta, Cr, Au, Ag, Pt, and
25 materials of the same kind as a material making said
catalyst particle.

4. The electron-emitting device according to Claim 1, wherein said fibrous carbon consists of a graphite nanofiber, a carbon nanotube, an amorphous carbon, or a mixture thereof.

5

5. The electron-emitting device according to Claim 1, wherein said fibrous carbon comprises a graphen.

10

6. The electron-emitting device according to Claim 1, wherein said fibrous carbon comprises a plurality of graphens.

15

7. The electron-emitting device according to Claim 6, wherein said plurality of graphens are layered in an axis direction of said fibrous carbon.

20

8. The electron-emitting device according to Claim 1, wherein said catalyst particle consists of Pd, Ni, Fe, Co, or an alloy thereof.

25

9. The electron-emitting device according to Claim 1, wherein an electron emission position from said fibrous carbon is more distant from a surface of said substrate than a position of a surface of said extraction electrode.

10. The electron-emitting device according to Claim 1, wherein said extraction electrode and negative electrode are formed on a surface of substantially planar shape of said substrate and a thickness of said negative electrode is larger than a thickness of the extraction electrode.

11. The electron-emitting device according to Claim 1, wherein said substrate is thicker in a region where said negative electrode is formed than in a region where said extraction electrode is formed.

12. The electron-emitting device according to Claim 1, wherein said conductive layer is formed from on said negative electrode to inside of the gap between said extraction electrode and negative electrode on a surface of said substrate.

13. An electron source wherein a plurality of electron-emitting devices as set forth in either one of Claims 1 to 12 are arrayed.

14. The electron source according to Claim 13, wherein said plurality of electron-emitting devices are electrically connected to a matrix wiring pattern.

15. An image-forming apparatus wherein an image-

forming member for forming an image by collision of emitted electrons is disposed at a position where the image-forming member faces the electron source as set forth in Claim 13.

5

16. An electron-emitting device comprising:

(A) a first electrode and a second electrode placed in opposition to each other with a gap between said first and second electrodes on a surface of a substrate; and

10

(B) a plurality of fibers electrically connected to said first electrode and comprising carbon as a main component,

wherein said fibers are placed on a surface of said first electrode facing said second electrode.

15

17. The electron-emitting device according to Claim 16, wherein each of the fibers comprising the carbon as a main component comprises a graphen.

20

18. The electron-emitting device according to Claim 16, wherein each of the fibers comprising the carbon as a main component comprises a plurality of graphens.

25

19. The electron-emitting device according to Claim 18, wherein said plurality of graphens are

layered in an axis direction of the fiber comprising carbon as a main component.

20. The electron-emitting device according to
5 Claim 16, wherein electrons are emitted by applying a voltage between said second electrode and said first electrode so that a potential of said second electrode is higher than that of the first electrode.

10 21. The electron-emitting device according to Claim 16, wherein a height from said substrate surface to said fibers is larger than a height from said substrate surface to a surface of the second electrode.

15 22. The electron-emitting device according to Claim 16, wherein a thickness of said first electrode is larger than a thickness of said second electrode.

20 23. The electron-emitting device according to Claim 16, wherein a first layer is placed between said first electrode and said fibers and said first layer comprises a Ti oxide, a Zr oxide, or an Nb oxide on a surface thereof.

25 24. The electron-emitting device according to Claim 23, wherein said fibers comprising carbon as a main component are fibers grown through a catalyst

material placed on said first layer.

25. The electron-emitting device according to
Claim 24, wherein said catalyst material is either of
5 Pd, Ni, Fe, Co, or an alloy thereof.

26. The electron-emitting device according to
Claim 23, wherein said first layer is electrically
conductive.

10

27. The electron-emitting device according to
Claim 23, wherein said first layer is covered by a
second layer over the surfaces other than a surface
facing said second electrode and said second layer
15 consists of a material on which no substantial growth
of fibers comprising carbon as a main component occurs
as compared with said first layer.

28. The electron-emitting device according to
20 Claim 23, wherein said first layer is covered by a
second layer over the surfaces other than a surface
facing said second electrode and said second layer
consists of a material selected from Ta, Cr, Au, Ag,
Pt, and materials of the same kind as a catalyst
25 material.

29. An electron source wherein a plurality of

electron-emitting devices as set forth in either one of
Claims 16 to 28 are arrayed.

30. An image-forming apparatus comprising the
5 electron source as set forth in Claim 29, and a
fluorescent member.

ABSTRACT OF THE DISCLOSURE

Provided are electron-emitting devices, electron sources, and image-forming apparatus improved in electron emission efficiency and in convergence of trajectories of emitted electrons. An electron-emitting device has a first electrode and a second electrode placed in opposition to each other with a gap between first and second electrodes on a surface of a substrate, and a plurality of fibers electrically connected to the first electrode and containing carbon as a main component, and the fibers are placed on a surface of the first electrode facing the second electrode.

FIG. 1A

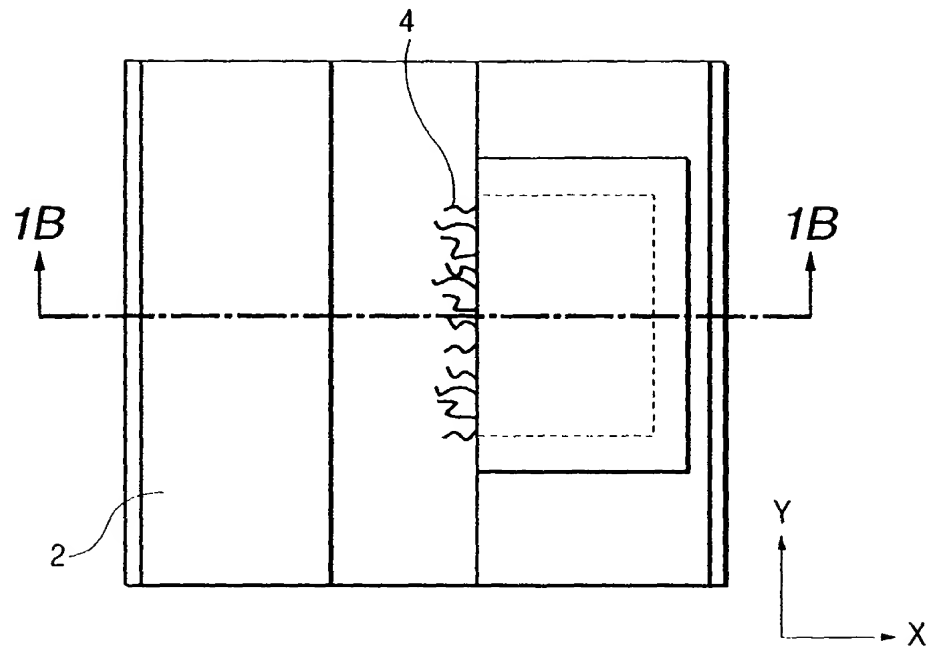


FIG. 1B

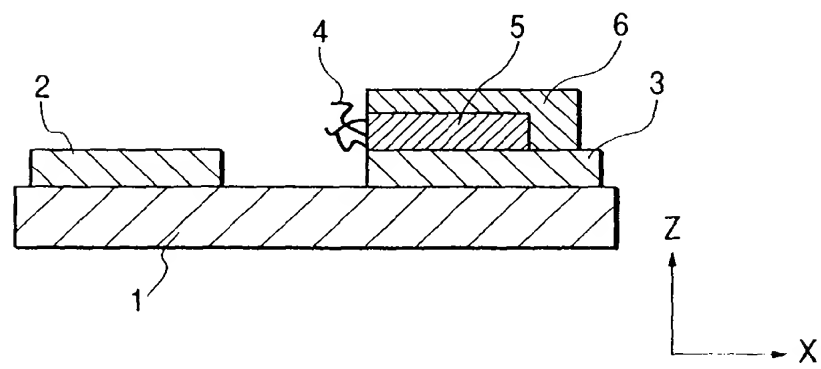


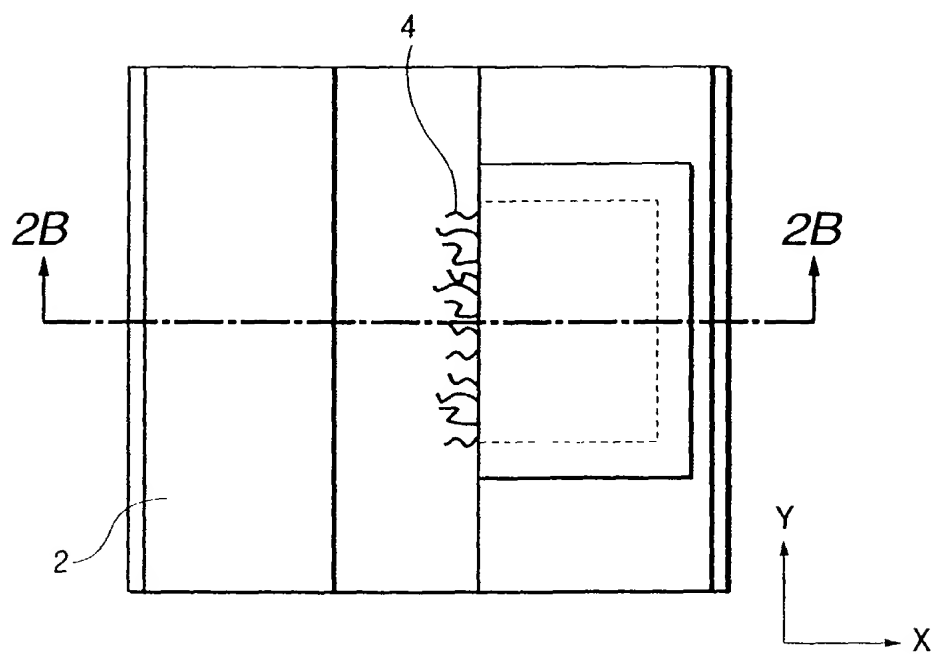
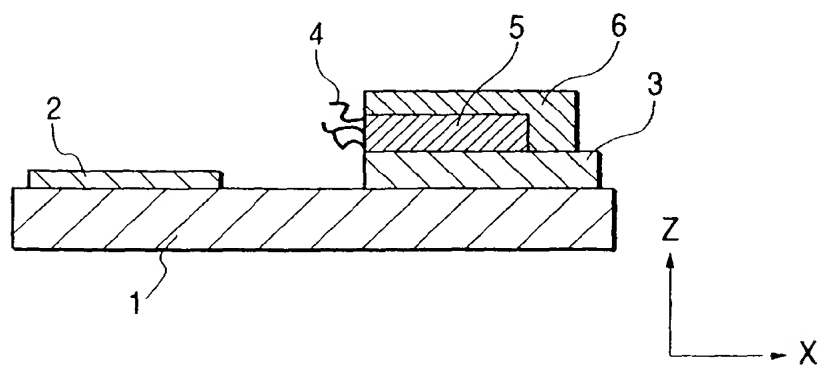
FIG. 2A*FIG. 2B*

FIG. 3A

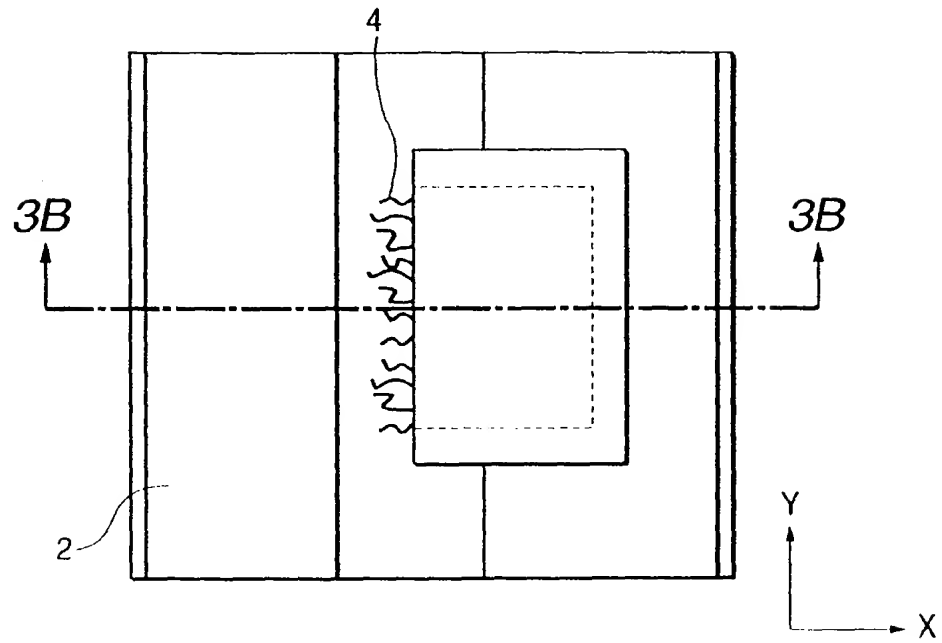


FIG. 3B

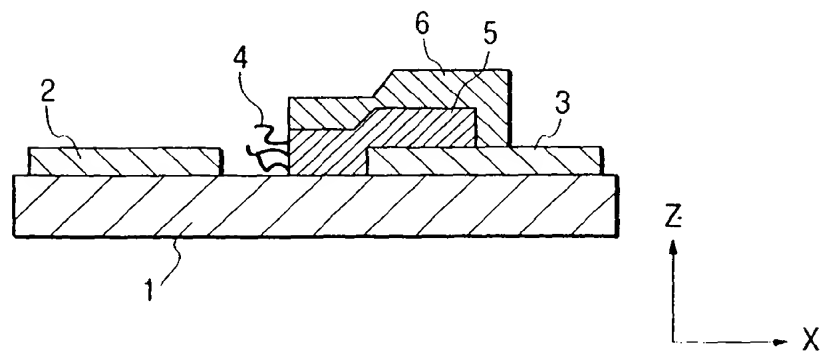


FIG. 4A

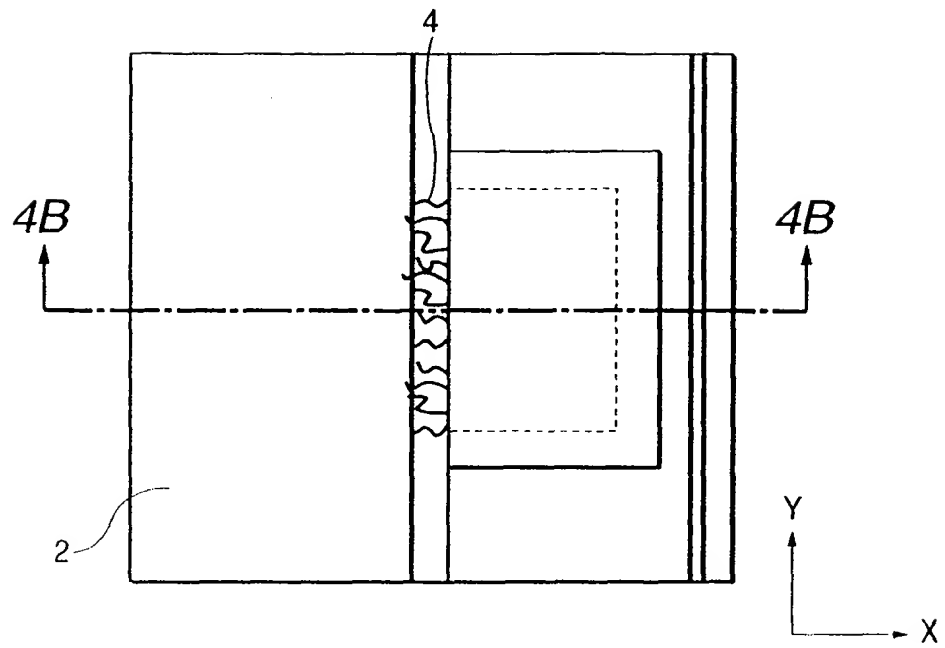


FIG. 4B

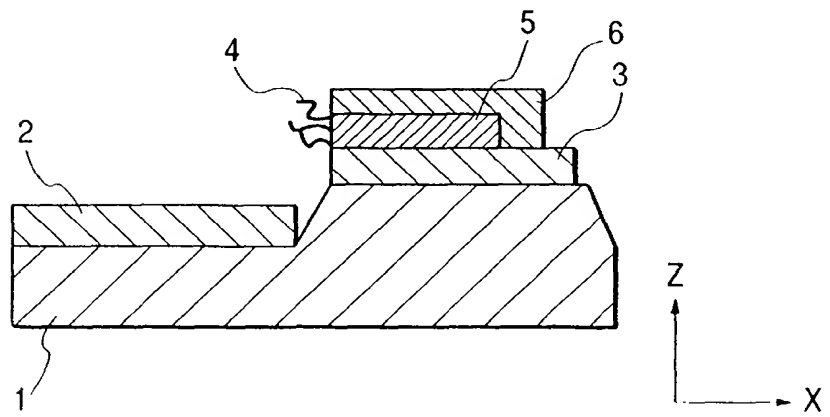


FIG. 5A

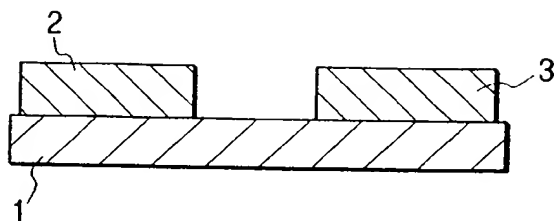


FIG. 5B

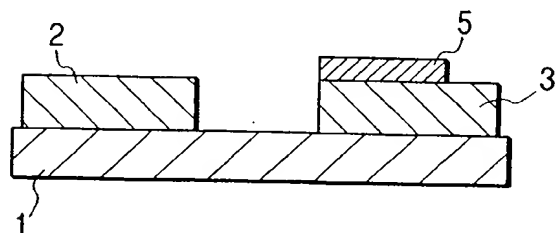


FIG. 5C

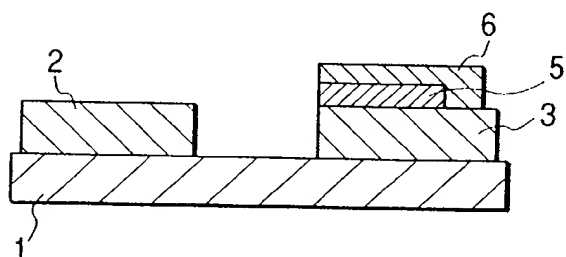


FIG. 5D

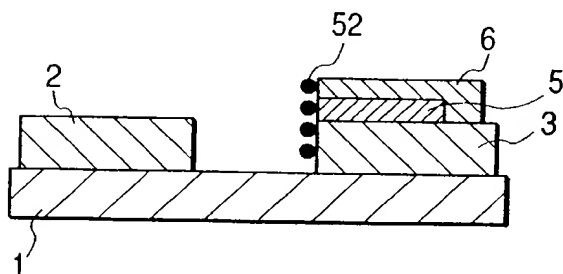


FIG. 5E

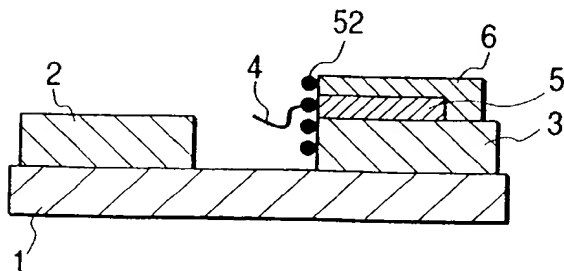


FIG. 6

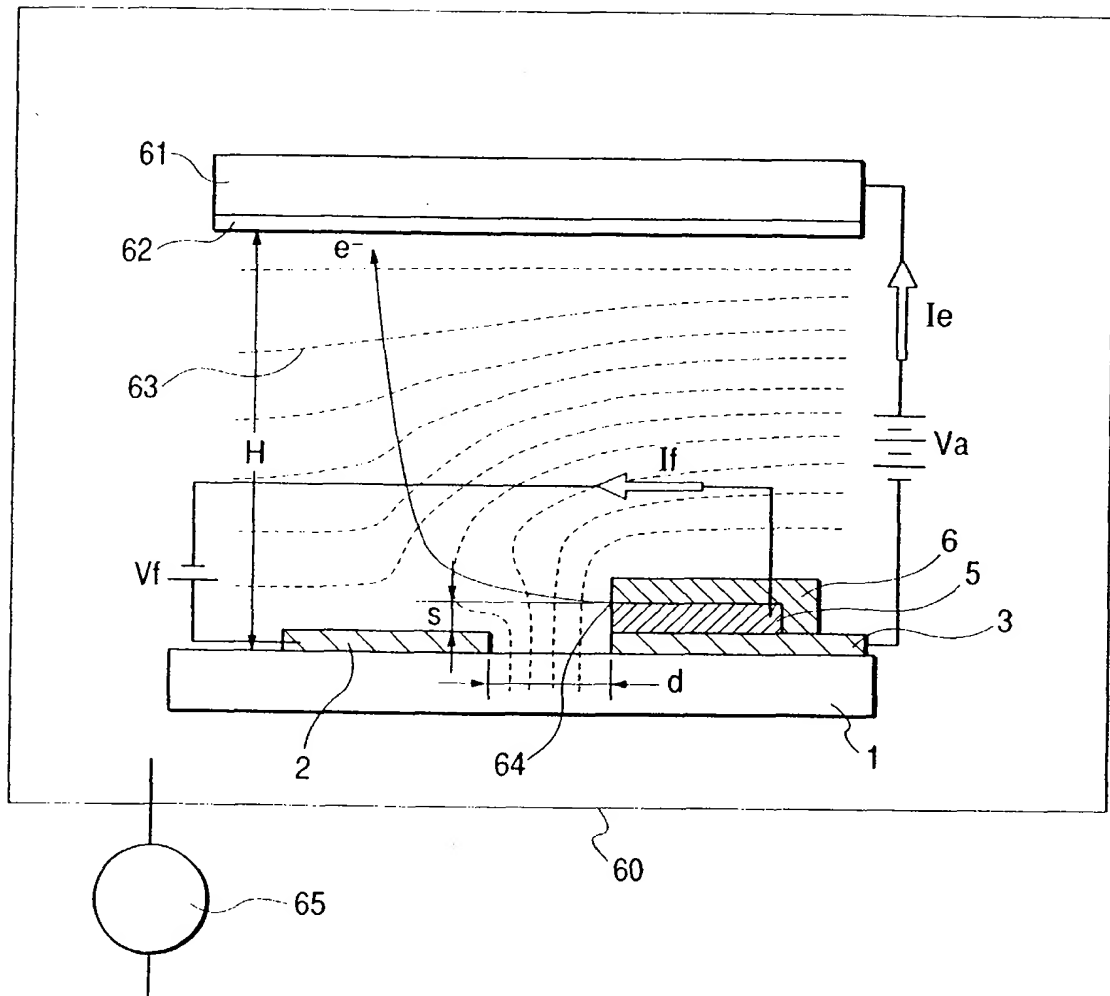


FIG. 7

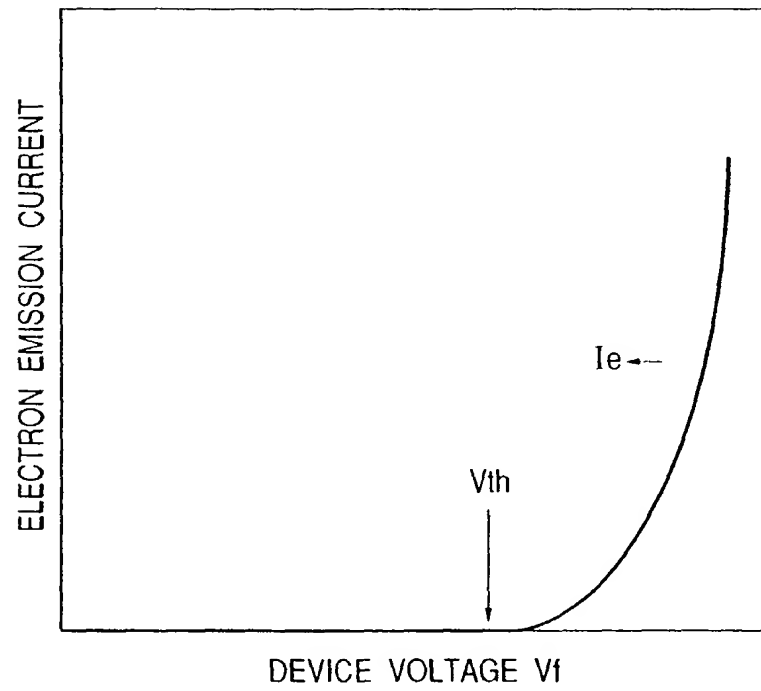


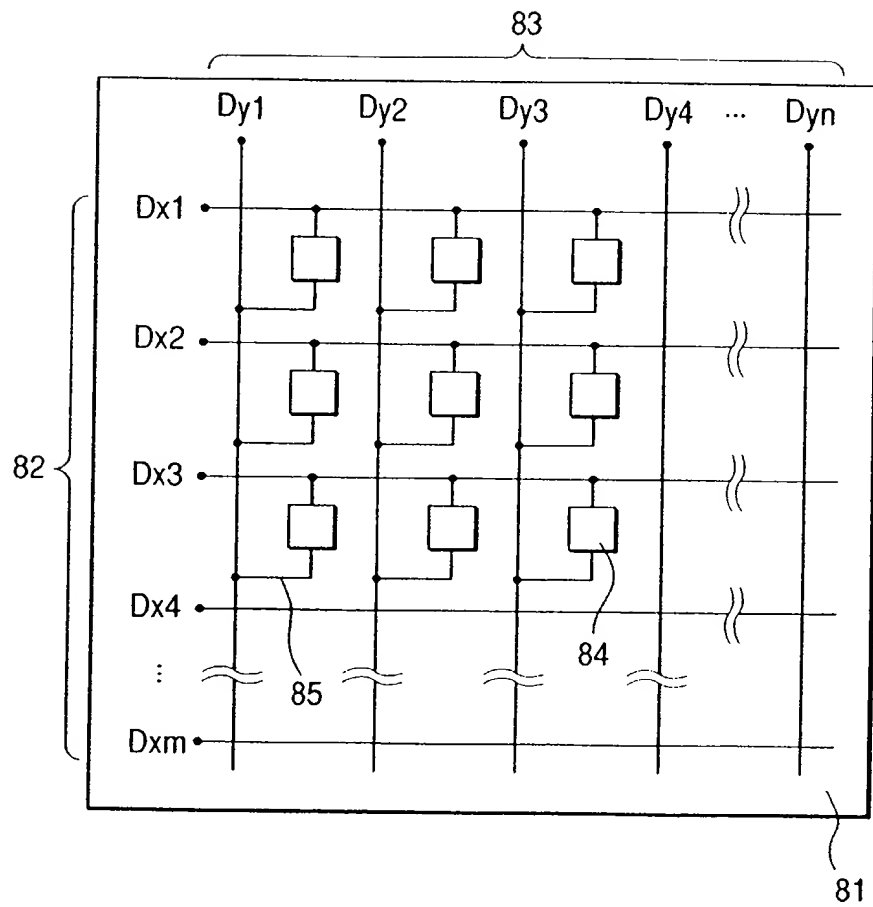
FIG. 8

FIG. 9

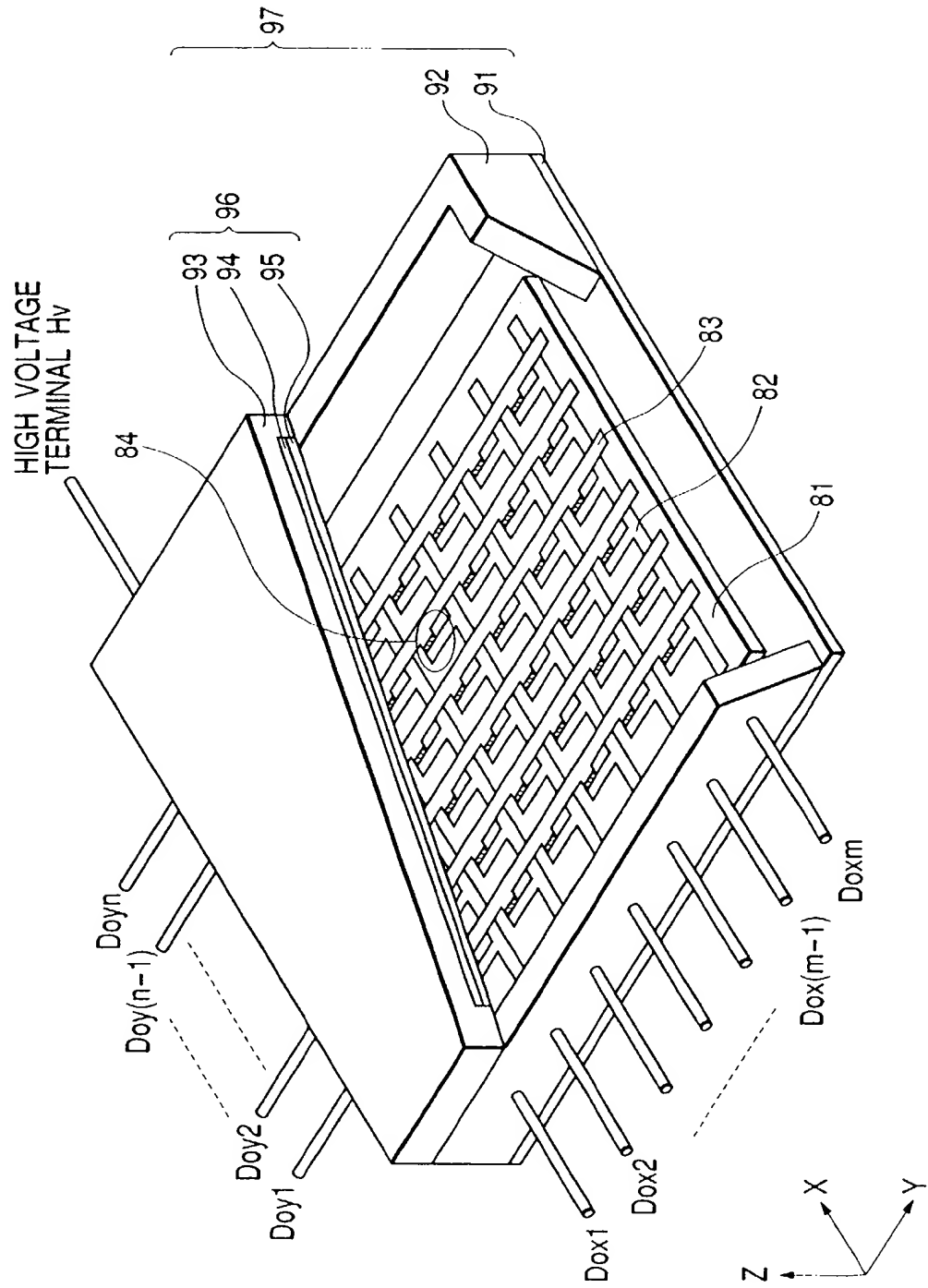


FIG. 10

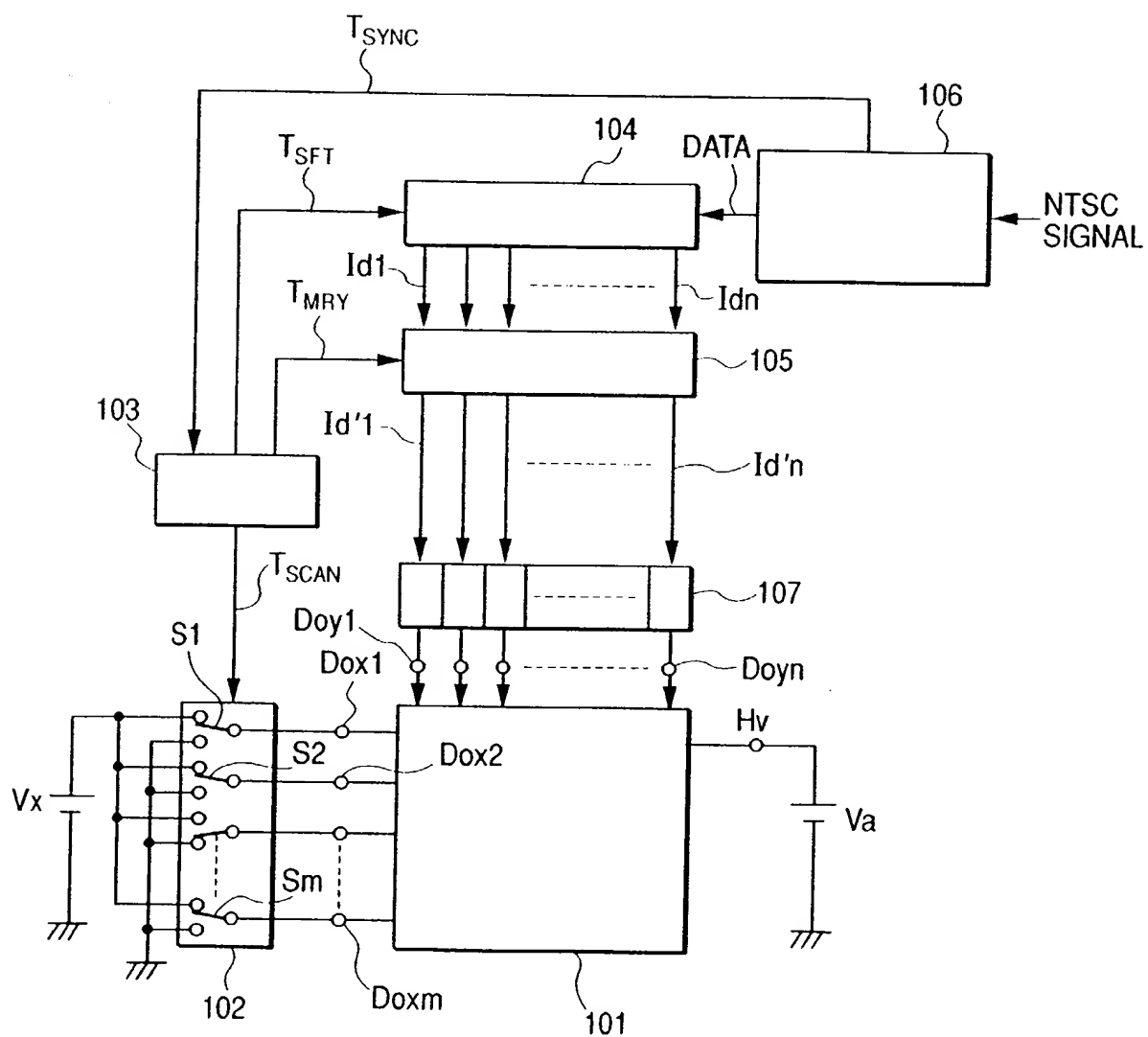


FIG. 11

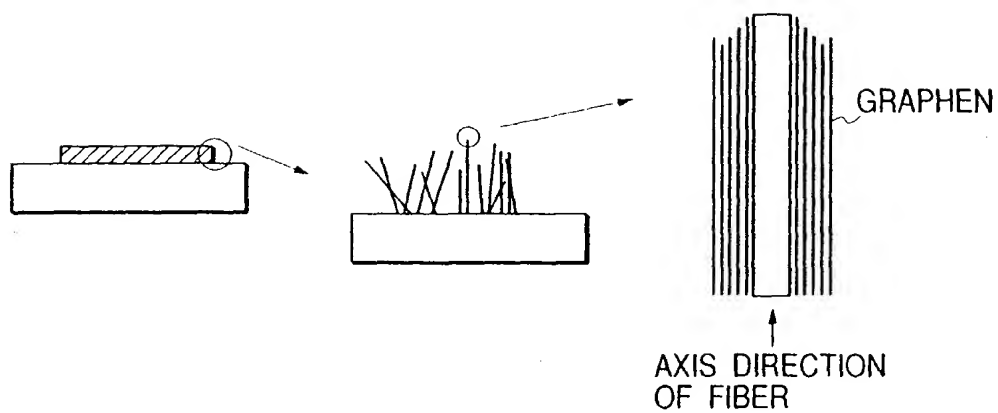


FIG. 12

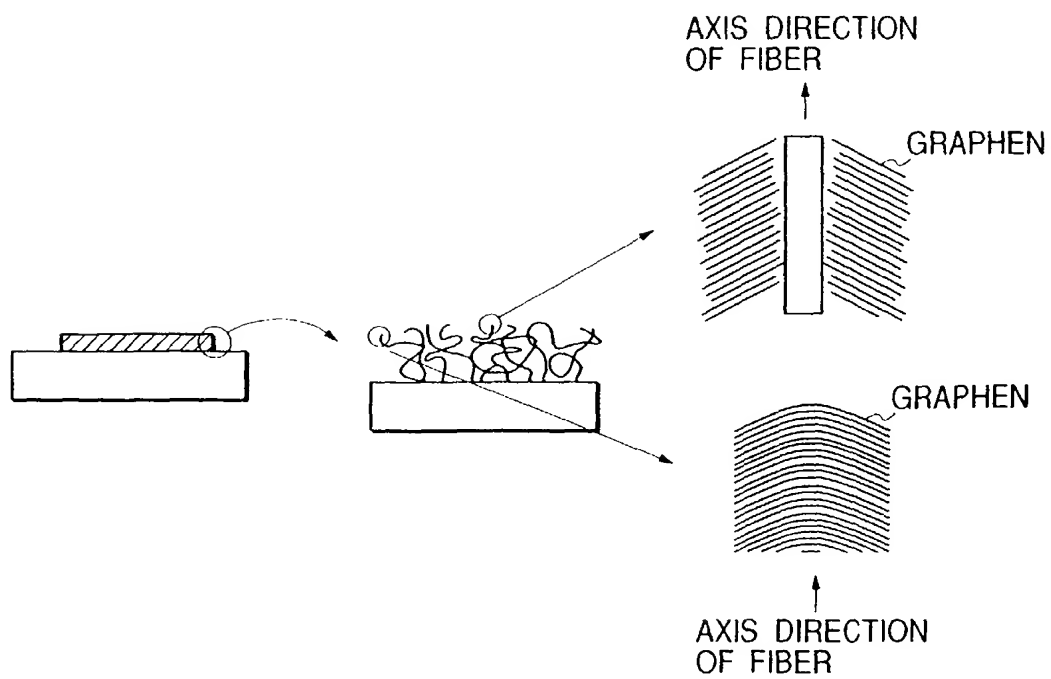


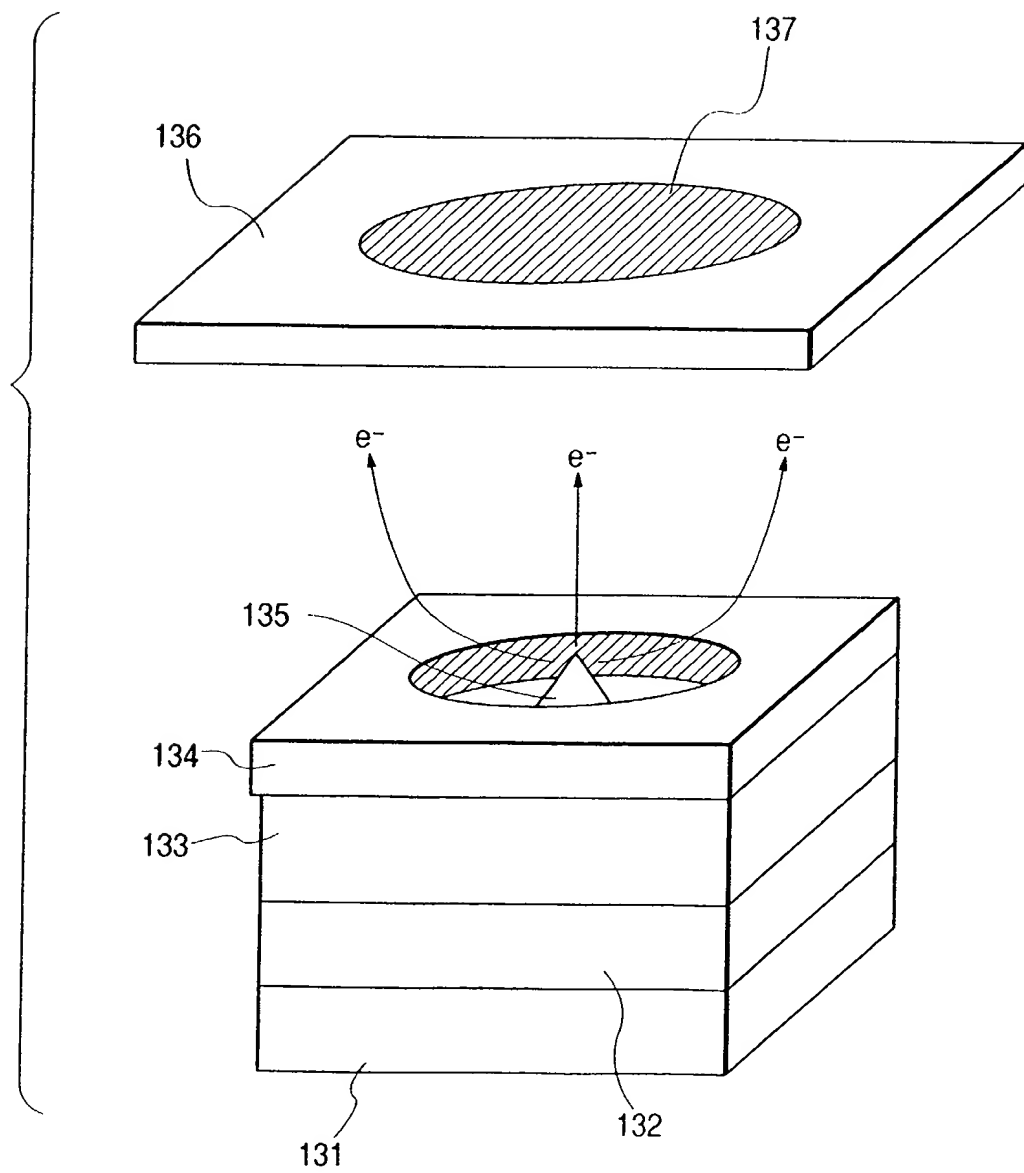
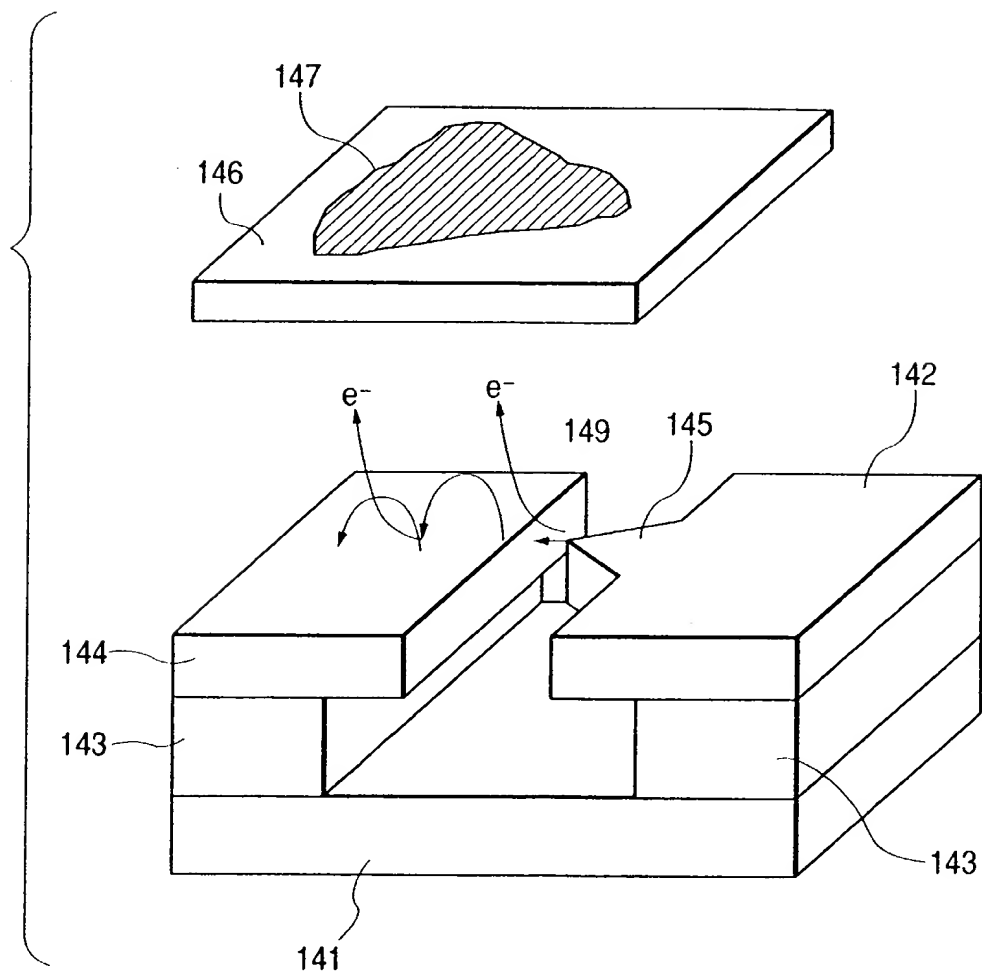
FIG. 13

FIG. 14

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ELECTRON-EMITTING DEVICE, ELECTRON SOURCE, IMAGE-FORMING APPARATUS, AND METHOD FOR PRODUCING ELECTRON-EMITTING DEVICE AND ELECTRON-EMITTING APPARATUS

5 BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to an electron-emitting device, an electron source using therewith, an image-forming apparatus, and a method for producing an electron-emitting device.

10

Related Background Art

A field emission type (FE-type) electron-emitting device for emitting an electron from a metal surface with a strong field over 10^6 V/cm applied to the metal has attracted attention as one of the effective cold electron sources.

15

If an FE-type cold electron source is put to practical use, a thin-type emissive image display device can be realized, thereby contributing to a power saving and lightweight system.

20

FIG. 12 shows a vertical FE-type structure. In FIG. 12, reference numeral 121 denotes a substrate, reference numeral 123 denotes an emitter electrode, reference numeral 124 denotes an insulation layer, reference numeral 125 denotes an emitter, reference numeral 126 denotes an anode, and reference numeral 127 denotes the shape of an electron beam emitted to the

25

anode. An aperture is formed in the layers of the insulation layer 124 and a gate electrode 122 arranged on the cathode electrode 123. The conical emitter 125 is provided in the aperture (the structure is hereinafter referred to as a Spindt type structure). The structure is disclosed by, for example, C. A. Spindt, "Physical Properties of thin-film field emission cathodes with molybdenum cones", J. Appl. Phys., 47,5248 (1976), etc.

Furthermore, an example of a lateral FE-type electron-emitting device can be formed by an emitter electrode having a pointed end and a gate electrode (extracting electrode) for extracting an electron from the end of the emitter electrode arranged parallel to the substrate with a collector (referred to as an anode in the present invention) provided in the direction vertical to the opposing direction of the gate electrode and the emitter electrode.

An example of an electron-emitting device using a fibrous carbon is disclosed by Japanese Patent Application Laid-Open No. 8-115652, Japanese Patent Application Laid-Open No. 2000-223005, European Patent Publication EP-A1-1022763, etc.

SUMMARY OF THE INVENTION

In the image-forming apparatus using the above mentioned FE-type electron source, an electron beam

spot (hereinafter referred to as a beam diameter) can be obtained depending on the distance H from the electron source to the phosphor, the anode voltage V_a between the electron-emitting device and the phosphor, the device voltage V_f between the cathode electrode and the leading electrode. The above mentioned beam span is submillimeter, and has sufficient resolution as an image-forming apparatus.

However, in the image-forming apparatus such as an image display device, etc., resolution with higher precision has been requested recently.

Furthermore, with an increasing number of displayed pixels, power consumption has risen from a large device capacity of the electron-emitting device when it is driven. Therefore, it has been demanded to reduce the device capacity and the device voltage, and improve the efficiency of the electron-emitting device.

Furthermore, it is necessary to have uniform characteristic of the electron-emitting device to avoid uneven distribution of the brightness among the pixels due to the uneven characteristics of the electron-emitting devices.

As a result, it is requested to reduce the capacity of a device, the device voltage, and the uneven characteristics among electron-emitting devices.

In the Spindt-type electron-emitting device shown in FIG. 12, a parasitic capacity has been formed

between a large gate capacity and a number of emitters
125 by the layer structure of a gate electrode 122 and
a substrate 121. Furthermore, the device voltage of
the spindt-type FE is as high as several tens of V,
5 thereby causing the problem of large power consumption
from a large capacity.

Additionally, since extracted electron beams
diffuse, a focusing electrode has been required to
suppress the diffusion of the beams. For example,
10 Japanese Patent Application Laid-Open No. 07-006714
discloses a method of focusing the trajectory by
providing an electrode for focusing electrons.
However, this method has the problem that the process
step of assigning the focusing electrode is
15 complicated, and that the electron emission efficiency
is low.

Furthermore, since a common horizontal FE is
designed such that an electron emitted from a normal
cathode easily crashes against the gate electrode, the
20 efficiency (the ratio of the electric current flowing
through a gate to the electric current reaching the
anode) is lowered, and the beams largely diffuse at the
anode.

With electron-emitting devices formed by a set of
25 fibrous carbon, local electron emission (electric field
concentration) is apparent when there are large
differences in length and shape among the devices.

Therefore, the current density accompanied by the electron emission becomes high at a portion where local electric field concentration arises, thereby possibly deteriorating the electron emission characteristic and shortening the life of the device.

Additionally, with the image-forming apparatus having a plurality of the above mentioned devices, the above mentioned events cause the apparent distribution of the amount of I_e (emission current) of each electron-emitting device, thereby reducing the performance of the image-forming apparatus by resulting in the poor display of gray scale images, flickering images, etc.

The present invention has been developed to solve the above mentioned problems, and aims at providing a durable electron-emitting device, electron source, image-forming apparatus having a uniform display characteristic for a long period, and a method for easily producing the electron-emitting device and the image-forming apparatus by guaranteeing a uniform electron emission characteristic.

To attain the above mentioned purpose, the method for producing an electron-emitting device according to the present invention includes on the surface of a substrate the steps of: arranging a cathode electrode; arranging an electrode opposite the cathode electrode; arranging a plurality of fibers mainly made of carbon

on the cathode electrode; and applying higher potential to the electrode opposite the cathode electrode than the potential applied to the cathode electrode under the depressurized condition.

5 Another method for producing the electron source according to the present invention to attain the above mentioned purpose includes the steps of: arranging on the substrate a plurality of electron-emitting devices each having a plurality of fibers mainly made of
10 carbon, and a plural pieces of wire each being electrically connected to at least one of the plurality of electron-emitting devices; applying a voltage to at least a part of the plurality of electron-emitting devices and measuring the electric characteristic of
15 the electron-emitting device to which the voltage has been applied; and reducing the difference in electric characteristic among the plurality of electron-emitting devices based on the measurement result. The step of reducing the difference in characteristic among the
20 above mentioned plurality of electron-emitting devices includes the step of allowing electrons to be emitted from at least one of the plurality of electron-emitting devices under the depressurized condition.

 Furthermore, it is preferable that the step of
25 emitting an electron from the above mentioned electron-emitting device is performed under the condition of a gas physically or chemically reactive to the fiber. In

this process, the portion where an electric field concentrates in the fiber is made to be reactive for a partial etching process. As a result, the stable and uniform electron-emitting device, electron source, and
5 image-forming apparatus can be produced.

It is preferable that the gas chemically reactive to the fiber contains H_2 , H_2O , O_2 , or CO_2 . Otherwise, it is desired that the gas chemically reactive to the fiber is a combination of H_2 gas and one of H_2O , O_2 , and
10 CO_2 gas.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A, 1B, 1C, 1D and 1E show a method for producing an electron-emitting device according to the
15 first embodiment;

FIGS. 2A and 2B show a step of equalizing the shapes of fine projections among the electron-emitting devices according to an embodiment of the present invention;

20 FIGS. 3A and 3B show an electron-emitting device according to the embodiment of the present invention;

FIGS. 4A, 4B, 4C and 4D show the step of producing the electron-emitting device according to the embodiment of the present invention;

25 FIGS. 5A and 5B show a change with time of an emission current of an electron-emitting device;

FIG. 6 shows an example of the configuration when

an electron-emitting device is operated;

FIG. 7 shows an example of the operation characteristic of an electron-emitting device according to the embodiment of the present invention;

5 FIG. 8 shows an example of the configuration of a simple matrix circuit according to the embodiment of the present invention;

FIG. 9 shows an example of the configuration of an image-forming apparatus using the electron source according to the embodiment of the present invention;

10 FIG. 10 shows the outline of the structure of a carbon nanotube;

FIG. 11 shows the outline of the structure of a graphite nanofiber;

15 FIG. 12 shows the conventional vertical FE-type electron-emitting device;

FIG. 13 shows the type of an equalizing process according to the present invention; and

FIG. 14 shows the type of another equalizing process according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The preferred embodiments of the present invention are described below in detail by referring to the attached drawings. However, the present invention is not limited to the dimensions, materials, shapes, and relative arrangements of the components of the

25

embodiments unless otherwise specified.

Described first below is the equalizing process of the electron emission characteristic of an electron-emitting device.

5 According to the present invention, it is most desirable to use fibrous carbon as an electron-emitting member of an electron-emitting device. Since fibrous carbon has a very large aspect ratio, it easily enhances an electric field. Therefore, it is possible
10 to emit an electron at a low voltage, and the fibrous carbon is recommended as an electron-emitting member according to the present invention.

 The "fibrous carbon" according to the present invention can refer to a "columnar substance chiefly
15 made of carbon" or "linear substance chiefly made of carbon". Furthermore, the "fibrous carbon" can also be referred to as "fiber chiefly made of carbon". To be more practical, the "fibrous carbon" according to the present invention also includes carbon nanotube,
20 graphite nanofiber, and amorphous carbon fiber. Especially, graphite nanofiber is the most desirable as an electron-emitting member.

 However, when the fibrous carbon is used as an electron-emitting member, it is frequently used as a
25 set of plural pieces of fibrous carbon in consideration of the production method. Since it is very difficult to equalize the shapes of the fibrous carbon in

thickness, length, etc., there often occurs unevenness
in characteristic among the electron-emitting devices
if the set of plural pieces of fibrous carbon is used
as an electron-emitting member of an electron-emitting
5 device.

Under the situation, according to the present
invention, a process of reducing the difference in
electron emission characteristic among electron-
emitting devices (equalizing process) is performed to
10 control the electron emission characteristic of the
electron-emitting device in which plural pieces of
fibrous carbon is used as an electron-emitting member.

The "equalizing process" which is the
characteristic of the method for producing the
15 electron-emitting device according to the present
invention is performed by applying a voltage to an
electron-emitting device after arranging plural pieces
of fibrous carbon on the electrode (cathode electrode)
to which potential, which is lower than the potential
20 to the opposite electrode (extracting electrode) in a
pair of electrodes forming the electron-emitting device
when the device is driven, is applied.

This method is especially convenient and effective
when an electron source, an image-forming apparatus,
25 etc. are formed using a plurality of electron-emitting
devices.

The "equalizing process" according to the present

invention not only reduces the difference in electron emission characteristic among a plurality of electron-emitting devices, but also improves the electron emission characteristic of one electron-emitting device.

That is, the electron-emitting device immediately after forming fibrous carbon indicates the difference in shape among plural pieces of fibrous carbon. Such a device can form a portion where an electric field specifically concentrates. When such an electron-emitting device having specific electric field concentration is operated, electrons are emitted with concentration from the specific portion, and a load is excessively generated in the portion. As a result, the electron emission characteristic is suddenly damaged, and no sufficient performance of an electron-emitting device can be obtained.

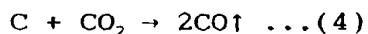
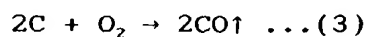
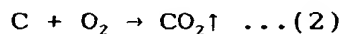
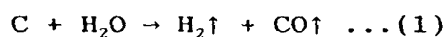
Therefore, by performing the "equalizing process" according to the present invention, the portion in which an electric field specifically concentrates can be removed, and electrons are substantially equally emitted from a number of pieces of fibrous carbon (the number of electron emission sites is increased). As a result, electron-emitting devices having an excellent electron emission characteristic and stable for a long period can be obtained.

It is desired that the above mentioned "equalizing

process" according to the present invention is performed by applying a voltage to a device under the condition of a substance reactive to the fibrous carbon.

5 The principle of the equalizing process is performed by an etching operation using the heat generated when an electron is emitted from the fibrous carbon, which is an electron-emitting portion, into a vacuum. In addition, when the process is performed
10 under the condition of the substance reactive to fibrous carbon, the reactive substance in the condition and the fibrous carbon are selectively reactive to each other, thereby performing a partial etching process.

 Since the fibrous carbon chiefly contains carbon,
15 the following reactions occur.



20 Therefore, H_2O , CO_2 , O_2 , H_2 , etc. can be useful as substances reactive to the fibrous carbon.

 FIGS. 2A and 2B shows the type of the equalizing process according to the present invention using a lateral electron-emitting device in which fibrous
25 carbon is used as an electron-emitting member.

 In FIGS. 2A and 2B, reference numeral 1 denotes an insulating substrate, reference numeral 2 denotes a

extracting electrode (also referred to as a "second
electrode" or "gate electrode"), reference numeral 3
denotes a cathode electrode (also referred to as a
"first electrode" or "negative electrode"), reference
5 numeral 4 denotes an electron-emitting member
comprising plural pieces of fibrous carbon electrically
connected to the cathode electrode. Reference numeral
20 denotes a vacuum chamber, reference numeral 21
denotes a substrate holder, reference numeral 22
10 denotes a gas leading valve, reference numeral 23
denotes vacuum pump, reference numeral 24 denotes an
anode (also referred to as a "third electrode"), and
reference numeral 25 denotes an equipotential surface.

In this example, a lateral electron-emitting
15 device is described, but the producing method according
to the present invention is also applicable to a
vertical electron-emitting device in which fibrous
carbon is used as an electron-emitting member.
Furthermore, since a lateral electron-emitting device
20 is simpler in production, and smaller in capacity in
the driving operation than the vertical electron-
emitting device, a high-speed driving process can be
performed.

Furthermore, although the vertical electron-
25 emitting device shown in FIG. 12 includes a cathode
electrode 123 and an extracting electrode (gate
electrode) 125, the fibrous carbon can emit electrons

in a low electric field. Therefore, the present invention can also be applied to a vertical electron-emitting device without a gate electrode 125 and an insulating layer 124 shown in FIG. 12. That is, the
5 present invention can be applied to an electron-emitting device configured by the cathode electrode 123 provided on the substrate 121 and fibrous carbon provided thereon.

In the vertical electron-emitting device, an
10 "equalizing process" can be performed by performing the voltage applying process similar to the process performed in the "equalizing process" described later, for applying the voltage between the cathode electrode (reference numeral 123 shown in FIG. 12) where the
15 fibrous carbon is arranged and the anode (reference numeral 126 shown in FIG. 12). Otherwise, an "equalizing process" can also be performed by performing the process similar to the voltage applying process performed in the "equalizing process" described
20 later, for applying the voltage between the extracting electrode (reference numeral 122 shown in FIG. 12) and the cathode electrode provided between the cathode electrode (reference numeral 123 shown in FIG. 12) where the fibrous carbon is arranged and the anode
25 (reference numeral 126 shown in FIG. 12).

Furthermore, an "equalizing process" can also be performed by arranging an electrode plate above the

cathode electrode where the fibrous carbon is provided,
and performing a voltage applying process similar to
the voltage applying process performed in the
"equalizing process" described later between the
5 electrode plate and the cathode electrode.

The "equalizing process" introduces an "reactive
gas" reactive to the fibrous carbon from the gas
leading valve 22 after evacuating the vacuum chamber 20
by the vacuum pump 23. Then, a voltage is applied to
10 the electron-emitting member 4 of fibrous carbon such
that the extraction electrode 2 can be positive, and an
electron is emitted from the electron-emitting member 4
of fibrous carbon. Then, the electron-emitting member
4 of fibrous carbon proceeds with the above mentioned
15 reaction toward right by means of the heat from the
electron emission, etc., thereby etching the fibrous
carbon (FIG. 2A).

During the process of the above mentioned
reaction, the reactive gas on the left side is
20 incessantly introduced by the gas leading valve 22, the
product on the right is evacuated by the vacuum pump
23, and the above mentioned reaction expressions are
proceeding right.

Since the reaction can be reciprocal, a reaction
25 product is set to be immediately removed from the
reaction system.

Furthermore, it is recommended to reserve the time

to stop electron emission to promote the reaction
between the reactive gas and the electron-emitting
member. To attain this, it is desired that a pulse
voltage is applied between the electron-emitting member
5 4 and the extraction electrode 2.

Since the reaction is driven by the heat from the
electron emission, the portion of the electron-emitting
member 4 easily emitting an electron (in which an
electric field can be easily enhanced) reacts with
10 concentration to the heat and then be etched in the set
of fibrous carbon. As a result, the electric field can
be equally applied by an electron emission area by
removing the portion where the electric field has
excessively been concentrated.

15 FIG. 2B shows the type of the result of the
"equalizing process". After performing the "equalizing
process", the electric field difference applied to each
piece of fibrous carbon is reduced. That is, the
equipotential surface 25 which is largely distorted as
20 shown in FIG. 2A is reduced in distortion as shown in
FIG. 2B.

When an image-forming apparatus is provided, etc.,
the "equalizing process" can also be performed after
bonding an electron source substrate formed by a
25 plurality of electron-emitting devices each having
fibrous carbon and the wiring for use in driving the
electron-emitting devices with a face plate having an

image-forming member comprising a phosphor, etc., and forming a vacuum envelope (referred to as a sealing process).

5 In the above mentioned process, the performance of the electron-emitting device, electron source, and image-forming apparatus using plural pieces of fibrous carbon can be improved.

10 That is, the electron-emitting device according to the present invention prevents the local electric field concentration in the "equalizing process", thereby equalizing the electron emission characteristic, and suppressing the attenuation of the emission current by the overload from the high current density due to the local field concentration.

15 Therefore, the induction of discharge can be suppressed, the durability of the electron-emitting device can be elongated, and a stable electron emission current with small fluctuations with time can be maintained.

20 Then, since the electron emission current of each electron-emitting device can be stably maintained in the electron source and the image-forming apparatus including a plurality of electron-emitting devices, the durability of each pixel can be improved, the gray scale of an image can be successfully expressed, and
25 the flicker of the image can be avoided, thereby expressing equal display characteristic for a long

period.

Described below is an embodiment of the practical configuration according to the present invention.

FIGS. 3A and 3B show an example of the
5 configuration of the electron-emitting device on which the producing method according to the present invention works. FIG. 3A is a plan view of the electron-emitting device according to the present embodiment. FIG. 3B is a sectional view along 3B-3B shown in FIG. 3A.

10 In FIGS. 3A and 3B, reference numeral 1 denotes a substrate, reference numeral 2 denotes an extracting electrode, reference numeral 3 denotes a cathode electrode, and reference numeral 4 denotes an electron-emitting member. FIGS. 4A to 4D schematically show a
15 type of the method of producing an electron-emitting device according to the present embodiment. An example of the method of producing an electron-emitting device according to the present embodiment is described below by referring to FIGS. 4A to 4D.

20 The substrate 1 refers to quartz glass, glass whose impure contents such as Na, etc. are reduced and replaced with K, etc., sodalime glass, a layer structure obtained by applying SiO_2 on the silicon substrate, etc. in the spatter method, etc., and an
25 insulating substrate such as ceramics, etc. of alumina, etc. (FIG. 4A).

The extraction electrode (gate electrode) 2 and

the cathode electrode 3 are disposed on the insulating substrate 1 (FIG. 4B).

The extraction electrode 2 and the cathode electrode 3 are conductive, and can be formed by the common vacuum film-forming technology such as the evaporation method, the sputter method, etc. and the photolithography technology.

The material of the extraction electrode 2 and the cathode electrode 3 can be, for example, carbon, metal, metal nitride, metal carbide, metal boride, semiconductor, or metal compound semiconductor.

The thickness of the electrodes 2 and 3 can be set in the range from several tens nm to several μm . It is desired to use such a heat resistant material as carbon, metal, metal nitride, metal carbide, etc. If the potential can be reduced due to a thin electrode, or if the electron-emitting device is used in a matrix array, then a low resistance metal wiring material can be used in a portion not involved in the electron emission as necessary.

The distance between the extraction electrode 2 and the cathode electrode 3 can be determined depending on the device voltage driving the electron-emitting device between the extraction electrode 2 and the cathode electrode 3 such that the electron emission field can be one through ten times larger than the vertical field when the electron emission field

(lateral field) of the electron-emitting member 4 is compared with the vertical field required to form an image.

For example, when the distance between the anode
5 24 and the cathode electrode 3 is 2 mm, and 10 kV is applied, the vertical field is 5 V/ μ m. In this case, the distance and the device voltage are to be determined such that the electron emission field of the electron-emitting member to be used is larger than 5
10 V/ μ m, and corresponds to be the selected electron emission field.

The "lateral field" according to the present invention can be referred to as a "electric field practically parallel to the surface of the substrate
15 1", or a "electric field in the direction of the extraction electrode 2 opposite the cathode electrode 3.

The "vertical field" according to the present invention refers to an "electric field in the direction
20 substantially perpendicular to the surface of the substrate 1", or an "electric field in the direction of the substrate 1 opposite an anode electrode 61".

Then, the electron-emitting member 4 having an uneven surface is disposed on the cathode electrode 3
25 (FIG. 4C). The material used as the electron-emitting member 4 is a set of fibrous carbon. It is desired that the fibrous carbon is graphite fiber.

The above mentioned fibrous carbon has a threshold field of several V/ μ m. FIGS. 10 and 11 show an example of configurations of fibrous carbon suitable for the present invention. Each figure shows an embodiment at
5 an optical microscope level (approximately 1000 \times) on the left, an embodiment at a scanning electronic microscope (SEM) level (approximately 30,000 \times) in the center, and an embodiment at a transmission electronic microscope (TEM) level
10 (approximately 1 million \times) on the right.

As shown in FIG. 10, a cylindrical shape of graphen (multiple wall cylinder is referred to as a multiwall nanotube) is referred to as a carbon nanotube, and its threshold is the smallest when the
15 tip of the tube is opened.

FIG. 11 shows the fibrous carbon may be produced at a relatively low temperature. A fibrous carbon of this form is comprised of a lamination of graphens (which is thus sometimes called "graphite nanofiber"
20 and the ratio of the amorphous structure of which increases depending on the temperature). To be more practical, the graphite nanofiber indicates a fibrous substance in which graphens are layered (laminated) in the longitudinal direction (axial direction of fiber).
25 That is, as shown in FIG. 11, it is a fibrous substance in which plurality of graphens are arranged and layered (laminated) so as not to be parallel to the axis of the

fiber.

The other carbon nanotube is a fibrous substance in which graphens are arranged (in cylindrical shape) around the longitudinal direction (axial direction of fiber). In other words, it is a fibrous substance in which graphens are arranged substantially in parallel to the axis of the fiber.

One sheet of graphite is referred to as a "graphen" or a "graphen sheet". To be more practical, graphite is obtained by laying plural carbon sheets, a lamination in which carbon planes, each of which is a spread of regular hexagons consisting of covalent bonds of carbon atoms in sp^2 hybrid, are layered at intervals of distance of 3.354 Å. Each of the carbon planes is called a "graphen" or a "graphen sheet".

Either fibrous carbon has an electron emission threshold of 1 V to 10 V/ μ m and is recommendable as the material of the emitter (electron-emitting member) 4.

Especially, an electron-emitting device using a set of graphite nanofiber is not limited to the device structure according to the present invention shown in FIGS. 2 and 3, but can emit electrons in a low electric field, can obtain a large emission current, can be easily produced, and obtains an electron-emitting device having a stable electron emission characteristic. For example, a graphite nanofiber emitter is used, an electron-emitting device can be

obtained by preparing an electrode for controlling the electron emission from the emitter, and a light emitting apparatus such as a lamp, etc. can be formed using a light emission member emitting light by the
5 irradiation of an electron emitted from a graphite nanofiber. Furthermore, by arranging plural arrays of electron-emitting devices using the above mentioned graphite nanofiber and by preparing an anode electrode comprising a light emission member such as a phosphor,
10 etc., an image-forming apparatus such as a display, etc. can be configured. An electron-emitting device, a light emitting device, and an image-forming apparatus using graphite nanofiber can stably emit electrons without keeping the inside each device in a vacuum
15 state as in the conventional electron-emitting device. Furthermore, since electrons can be emitted in a low field, a reliable device can be easily produced. As a result, the producing method according to the present invention is more recommendable in the device using the
20 graphite nanofiber.

The above mentioned fibrous carbon can be formed by decomposing the hydrogen carbide gas using a catalyst (a material for promoting the pile of carbon). The carbon nanotube and the graphite nanofiber depend
25 on the type of catalyst and the temperature of decomposition.

As the catalyst material, Fe, Co, Pd, Ni, or an

alloy of any of the selected materials can be used as the nucleus forming the center of the fibrous carbon.

In particular, Pd, Ni may be material for generating graphite nanofiber at a low temperature (400°C or more). The temperature at which the carbon nanotube is generated using Fe or Co is over 800°C while the graphite nanofiber material can be generated at a low temperature. Therefore, it is desired from the viewpoint of the influence on other members and the production cost to generate graphite nanofiber material using Pd and Ni.

Furthermore, relating to Pd, using the characteristic of an oxide which is reduced at a low temperature (room temperature), paradium oxide can be used as a nucleus forming material.

When a hydrogen reduction process is performed on a paradium oxide, a fast condensation nucleus can be formed at a relatively low temperature (200° or lower) without thermal condensation of a thin metal film or generation and evaporation of super-particle conventional used as common nucleus forming technology.

The above mentioned hydrogen carbide gas can be, for example, ethylene, methane, propane, propylene, CO, CO₂ gas, or vapor of an organic solvent such as ethanol, acetone, etc.

Furthermore, the present invention can be applicable to any electron-emitting member 4 having an

uneven surface as shown in FIG. 4C. The material of the electron-emitting member 4 having an uneven surface can be a heat-resistant material such as W, Ta, Mo, etc., a carbide such as TiC, ZrC, HfC, TaC, SiC, WC, etc., a boride such as HfB₂, ZrB₂, LaB₆, CeB₆, YB₄, GdB₄, etc., a nitride such as TiN, ZrN, HfN, etc., a semiconductor such as Si, Ge, etc., carbon and carbon compound, etc. containing diffused amorphous carbon, graphite, diamond-like carbon, and diamond.

Such a electron-emitting member 4 having an uneven surface can be obtained by either the process of generating projections using a method of the RIE, etc. from a film piled in the common vacuum film-forming method, etc. such as the spatter method, etc. or the process of growing a pin-shaped crystal through the generation of a nucleus in the CVD, growing a whisker-shaped crystal, etc.

The control of the shape of the projections depends on the type of substrate to be used, the type of gas, the pressures of a gas (flow rate), an etching time, the energy when plasma is formed, etc. On the other hand, in the CVD forming method, control is performed based on the type of substrate, the type of gas, the flow rate, the growing temperature, etc.

Regardless of the relation to the electron emission, the area in which the electron-emitting member 4 is placed is referred to as an "electron

emission area" according to the present invention.

Then, the above mentioned electron-emitting member
4 is partially etched, and the "equalizing process"
increasing the number of emission sites is performed
5 (FIG. 4D).

After the electron-emitting device is provided in
the vacuum chamber 20 as shown in FIGS. 2A and 2B, and
the vacuum chamber 20 is evacuated by the vacuum pump
23, the gas leading valve 22 introduces a substance
10 chemically or physically reactive to the electron-
emitting member 4.

A chemically reactive substance can be the above
mentioned O_2 , CO , H_2O , H_2 , etc. when the electron-
emitting member 4 is carbon (fibrous carbon). It is
15 preferable that the gas chemically reactive to the
fiber is a mixed gas of a gas selected from among H_2O ,
 O_2 , CO_2 and H_2 gasses.

A substance physically reactive refers to a
substance which can be an electrified particle when an
20 electron beam crashes, and it is desired to have a
substance having a large mass such as Ar , etc. The
introduction pressure of a gas of the above mentioned
substance depends of the type of gas. However, when
the substance is chemically reactive, it is 1×10^{-4} Pa
25 or over. When the substance is physically reactive, it
is approximately 1×10^{-6} to 1×10^{-4} Pa.

If potential is applied to the electron-emitting

member 4 of the electron-emitting device such that the extraction electrode 2 of the electron-emitting device can be positive, and an electron is emitted after introducing the above mentioned gas, then the above
5 mentioned gas is reactive to the electron-emitting member 4 to etch the electron-emitting member 4.

In this step in the electron emission area, a portion in which electrons can be easily emitted (an electric field can be easily enhanced) becomes reactive
10 and etched with concentration, a portion in which an electric field has excessively concentrated can be removed, and the field can be more equally applied to the electron emission area.

FIGS. 2A and 2B show the type of this process.
15 FIG. 2A shows the type of the device when the "equalizing process" is started, and FIG. 2B shows the type of the device after performing the "equalizing process".

When an image-forming apparatus is formed, this
20 step can also be performed by: bonding the electron source substrate on which wiring, etc. is arranged for an electron-emitting device to the face plate having an image-forming member comprising a phosphor, etc.; introducing the reactive gas after forming an envelope
25 (referred to a sealing step); and applying positive potential to the anode in the electron emission area.

Thus, an electron-emitting device according to the

present embodiment can be formed.

The electron-emitting device and its operation obtained in the above mentioned steps are described below by referring to FIGS. 6 and 7. An electron-emitting device having a gap of several μm between the extraction electrode 2 and cathode electrode 3 is provided in a vacuum chamber 60 as shown in FIG. 6 to allow a vacuum pump 63 to completely perform an evacuation until achieving a pressure of about 10^{-5} Pa, the anode electrode 61 is provided at the height of H, which is several mm from the substrate 1, using a high voltage as shown in FIG. 6, and an anode voltage V_a , that is, a high voltage of several kV, is applied between the cathode electrode 3 and the anode electrode 61.

A phosphor 62 coated with a conductive film is provided on the anode electrode 61.

A device voltage V_f of a pulse voltage of several tens V is applied between the extraction electrode 2 and the cathode electrode 3 to measure a flowing device current I_f and an electron emission current I_e .

At this time, an equipotential line 66 is formed as shown in FIG. 6, and the point at which an electric field concentrates is located closest to the anode 61 of the electron-emitting member 4 indicated by 64, and inside the gap.

It is assumed that an electron is emitted from the

electron-emitting member 4 located near the electric field concentration point 64.

As shown in FIG. 7, the characteristic of the electron emission current I_e of the electron-emitting device shows I_e suddenly rising about half of the applied voltage (device voltage V_f), I_f having the characteristic similar to that of I_e , but having a sufficiently smaller value than I_e .

Furthermore, I_e observed when the electron-emitting member 4 is destroyed, etc. due to the local field concentration on the electron-emitting member 4 has not suddenly fluctuated.

FIG. 5A shows the I_e fluctuation when each of the devices A, B, and C according to the present embodiment produced in the same producing method is driven with V_f , V_a , and H set constant. It proves that the three devices A, B, and C indicate small fluctuation, and have similar I_e values.

For comparison, FIG. 5B shows the fluctuation of I_e (emission current) when each of the devices D, E, and F produced in the same producing method except omitting the equalizing process (shown in FIG. 4D) by the electron-emitting member 4 is driven. In the device D, a sudden drop of I_e is observed in the driving period. In the device F, I_e is stepwise reduced, and indicates a saturation tendency at a certain value. I_e of the device E is stable.

Thus, without performing the "equalizing process", the characteristic of devices are unequal because the devices have different portions where an electric field easily concentrates due to different configurations of fibrous carbon which is an electron-emitting member.

Listed below are examples of three devices (A, B, and C), and described below is an example of an equalizing process among a number of devices according to the present invention. FIG. 14 shows electron emission characteristics of different devices A to C before the "equalizing process".

In this example, the threshold V_{th3} of the electron emission is largest for the device C, and the threshold V_{th1} of the electron emission is smallest for the device A.

When the device A is driven with a pulse voltage under the condition of the above mentioned reactive gas, the mechanism of the above mentioned chemical etching of carbon suddenly reduces the electron emission current of the device A. The process is performed with the voltage applied to the device A gradually increased until the electron emission cannot be substantially detected when the threshold voltage (V_{th3}) of the device c is obtained. Similarly, the process is performed on the device B until the current value is reduced from the value indicated by the point A shown in the figure to the value indicated by the

point B.

Thus, if the characteristic of each device is evaluated under the condition after the reactive gas has been evacuated, the electron emission
5 characteristics of the devices A and B can substantially match the electron emission characteristic of the device C.

A preferable method as the "equalizing process" among a number of devices is described below. The
10 preferable method comprising the steps of: find the electron-emitting device whose threshold voltage required to emit an electron is determined to be low with the characteristic of other devices, and then make the threshold voltages of the other devices becomes
15 closer to the threshold of the device whose threshold voltage is determined to be low with the other devices.

An example of the method for performing the equalizing process on an electron source for which a plurality of electron-emitting devices are provided is
20 described below by referring to FIG. 8 based on the above mentioned principle. In FIG. 8, reference numeral 81 denotes an electron source substrate, reference numeral 82 denotes X direction wiring, reference numeral 83 denotes Y direction wiring,
25 reference numeral 84 denotes an electron-emitting device, and reference numeral 85 denotes a connection line.

X direction wiring 82 is formed by m pieces of wiring, that is, Dx1, Dx2, ..., Dxm, and can be configured by conductive metal, etc. formed in the vacuum evaporation method, the printing method, the
5 spattering method, etc. The material, the film thickness, the width of the wiring can be appropriately designed.

The Y direction wiring 83 is formed by n pieces of wiring, that is, Dy1, Dy2, ..., Dyn, which is similarly
10 formed in the X direction wiring 82.

Among the m pieces of X direction wiring 82 and n pieces of Y direction wiring 83, an inter-layer insulation layers (not shown in the attached drawings) for separating them, which layers separate both
15 electrically.

The inter-layer insulation layer not shown in the attached drawings is configured by SiO₂, etc. formed in the vacuum evaporation method, the printing method, the spattering method, etc. For example, it is formed in a
20 desired shape on all or a part of the electron source substrate 81 on which the X direction wiring 82 is arranged. Its film thickness, material, and producing method are appropriately designed to stand the potential difference at the crossing portion between
25 the X direction wiring 82 and the Y direction wiring 83.

The X direction wiring 82 and the Y direction

wiring 83 are led as external terminals.

A pair of electrodes (not shown in the attached drawings) forming the electron-emitting device 84 are electrically connected by m pieces of the X direction wiring 82, n pieces of the Y direction wiring 83, and the connection line 85 comprising conductive metal, etc.

When the number of rows in the X direction and the number of columns in the Y direction increase in the simple matrix as shown in FIG. 8, there occurs apparent distribution of the voltage applied to each device due to a drop of voltage if the "equalizing process" is collectively performed by selecting all of the electron-emitting devices 84 in the matrix. For example, it is desired that the "equalizing process" is performed with line (wiring) by line (wiring) or the "equalizing process" is performed with one by one (dot sequentially).

In this embodiment, an example of the equalizing process performed on all electron-emitting devices is described. However, the equalizing process can be performed not on all electron-emitting devices, but only on a desired electron-emitting device.

Before performing the equalizing process, it is desired that the electric characteristic of the electron-emitting device 84 is measured. It can be determined how the electric characteristic of each

electron-emitting device can be set based on the data obtained in the measurement. The electric characteristic to be measured (monitored) is obtained by measuring the current occurring when a predetermined
5 voltage is applied to each electron-emitting device or between the electron-emitting device and the anode.

A current occurring in an electron-emitting device can be a current flowing between an extraction electrode and a cathode electrode when a predetermined
10 voltage is applied between the extraction electrode and the cathode electrode of each electron-emitting device. A current occurring between the anode electrode and the electron-emitting device can be a current detected when
15 a current flowing to anode (emission current from the electron-emitting device) when a predetermined voltage is applied between the anode electrode and the electron-emitting device.

It is desired that the measurements of the electric characteristic are made on all electron-
20 emitting devices. However, when the number of electron-emitting device increases, measurements can be made only on limited devices, and the "equalizing process" can be performed based on the measurement value.

25 To have the electric characteristics of all electron-emitting devices close to a predetermined value range based on the measured electric

characteristic, it is desired to perform the
"equalizing process" on all electron-emitting devices.
However, if the electric characteristics of devices are
not quite different from each other, the "equalizing
5 process" can be performed only on the electron-emitting
device having the characteristic out of the desired
range.

Described below is the above mentioned method of
sequentially equalizing lines. For example, the
10 "equalizing process" is performed by commonly
connecting (for example, a GND connection) n pieces of
Y direction wiring, that is, $Dy1, Dy2, \dots, Dyn$,
applying positive potential to the Y direction wiring
to $Dx1$ of the X direction wiring, and selecting the
15 electron-emitting device at the row $Dx1$ (electron-
emitting device connected to the wiring of $Dx1$) 84.
Then, a similar voltage is applied to $Dx2$, the
electron-emitting device at the row $Dx2$ is selected,
and the "equalizing process" is performed. Similarly,
20 the rows $Dx3, Dx4, \dots, Dxm$ are sequentially selected,
and the equalizing process is performed in the X
direction in a line sequence. Thus, the influence of a
voltage drop can be reduced. In this embodiment, the
"equalizing process" is performed on all electron-
25 emitting devices connected to one piece of X direction
wiring. However, the "equalizing process" can be
performed on some of the electron-emitting devices

connected to one pieces of the X direction wiring.
That is, the "equalizing process" is not performed on
all electron-emitting devices, but can be performed
only on desired electron-emitting devices.

5 Then, in the "equalizing process" sequentially
performed one (device) by one (device), each device is
selected using the above mentioned matrix wiring using
the above mentioned matrix wiring so that it can be
independently driven, and the electron-emitting device
10 84 can be individually equalized. In this method,
there is no influence of a voltage drop, but the time
required to perform the process is proportional to the
number of the devices. Therefore, any of the line
sequence process, the point sequence process, and a
15 collective process can be performed depending on the
size or the use of an electron source. Also in this
method, the equalizing process is not performed on all
electron-emitting devices, but is performed only on
desired electron-emitting devices.

20 Described below is the image-forming apparatus
configured using the electron source of the above
mentioned simple matrix by referring to FIG. 9. FIG. 9
shows a type of an example of the display panel of the
image-forming apparatus.

25 In FIG. 9, reference numeral 81 denotes an
electron source substrate 81 for which a plurality of
electron-emitting devices are provided, reference

numeral 91 denotes a rear plate to which the electron source substrate 81 is fixed, reference numeral 96 denotes a face plate in which a fluorescent film 94, a metal back 95, etc. are formed inside a glass substrate

5 93. Reference numeral 92 denotes a support frame to which the rear plate 91 and the face plate 96 are bonded using frit glass, etc. Reference numeral 97 denotes an envelope can be formed and sealed by baking at the temperature of 400 to 500°C for over 10 minutes

10 in the vacuum or nitrogen.

As described above, the envelope 97 comprises the face plate 96, the support frame 92, and the rear plate 91. Since the rear plate 91 is provided mainly to reinforce the strength of the electron source substrate

15 81, the separate rear plate 91 is not required if the electron source substrate 81 itself is strong enough. That is, the support frame 92 can be bonded directly to the electron source substrate 81 so that the face plate 96, the support frame 92, and the electron source

20 substrate 81 can configure the envelope 97. On the other hand, a support unit, referred to as a spacer, not shown in the attached drawings can be provided between the face plate 96 and the rear plate 91 to configure the envelope 97 durable against the

25 atmosphere.

Furthermore, the "equalizing process" of the electron-emitting member 4 according to the present

embodiment can be performed by introducing a reactive gas using a gas lead tube 98 after forming the envelope 97. The lead gas and the reaction product can be removed at any time by an evacuation tube 99.

5 The image-forming apparatus according to the present embodiment can also be used as an image-forming apparatus, etc. as a display device such as a device for a television broadcast, video conference system, a computer, etc. and an optical printer configured by a
10 photosensitive drum, etc.

(Embodiments)

Described below in detail are practical embodiments according to the present invention.

(First Embodiment)

15 As the first embodiment of the present invention, an electron is emitted between the cathode electrode and the extraction electrode of the electron-emitting device under the condition of an O₂ gas, and the "equalizing process" is performed. FIGS. 1A to 1E show
20 a method of producing an electron-emitting device according to the present embodiment. FIGS. 3A and 3B are a plan view and a sectional view of the produced electron-emitting device. Described below is the step of producing the electron-emitting device according to
25 the present embodiment.

(Step 1 (FIG. 1A))

A quartz substrate is cleaned and used as the

substrate 1. 5 nm thick Ti and 30 nm thick Pt area are continuously evaporated in the sputter method as the extraction electrode 2 and the cathode electrode 3.

Then, in the photolithography process, a resist
5 pattern is formed using a positive type photoresist (AZ 1500 made by Clariant).

Next, the Pt layer and Ti layer dry etching processes are performed using Ar with the patterned photoresist as a mask, and the extraction electrode 2
10 and the cathode electrode 3 having the gap of 5 μm between the electrodes are formed.

(Step 2 (FIG. 1B))

Then, about 100 nm thick Cr is piled in the evaporating process. In the photolithography process,
15 a resist pattern is formed using a positive type photoresist (AZ 1500 made by Clariant).

Next, using the patterned photoresist as a mask, the area (100 μm square) for coating the electron-emitting member 4 is formed on the cathode electrode 3,
20 and the Cr of an aperture is removed by a cerium nitrate etching solution.

After removing the photoresist, a complex solution obtained by adding a Pd complex to isopropyl alcohol, etc. is applied by a spin coat.

25 After the application, a heat treatment is performed at 300°C in the atmosphere, about 10 nm thick palladium oxide 41 is formed on the cathode electrode

3, and then Cr is removed by the cerium nitrate etching solution.

(Step 3 (FIG. 1C))

The atmosphere is evacuated with the heat of
5 200°C, the heat treatment is performed in the flow of
the 2% hydrogen diluted by nitrogen. At this step, an
about 3 to 10 nm diameter particle 42 is formed on the
surface of the cathode electrode 3. At this time, the
density of the particle 42 is estimated to be about
10 10¹¹ to 10¹²/cm².

(Step 4 (FIG. 1D))

Then, in the flow of 0.1% ethylene diluted by
nitrogen, the heat treatment is performed at 500°C for
10 minutes. When this process is observed by a
15 scanning electronic microscope, it proves that a number
of pieces of fibrous carbon 43 extending as 10 to 25 nm
diameter curving fiber are formed on the Pd coated
area. At this time, the fibrous carbon 43 is about 500
nm thick.

20 (Step 5 (FIG. 1E))

Then, a device is provided in the vacuum device 20
shown in FIGS. 2A and 2B, the vacuum pump 23 performs
the evacuation up to 1×10^{-5} Pa, the gas leading valve
22 leads an O₂ gas until the vacuum level in the vacuum
25 device 20 reaches 1×10^{-4} Pa, and a pulse voltage is
applied to the cathode electrode 3 with the extraction
electrode 2 set positive. The system is driven for 1

hour in this state, and the electron-emitting member 4 is equalized.

The electron-emitting device is formed in the above mentioned steps, and completely evacuated by the evacuation device 63 in the vacuum device 60 shown in FIG. 6 until 2×10^{-6} Pa is reached, and an anode voltage $V_a = 10$ kV is applied to the anode electrode 61 H = 2 mm apart as shown in FIG. 6.

At this time, a pulse voltage of device voltage $V_f = 20$ V is applied to the electron-emitting device, and the flowing device current I_f and the electron emission current I_e are measured.

The I_e characteristic of the electron-emitting device shows a sudden increase of I_e from the half of the applied voltage, and the electron emission current I_e of about 1 μ A is measured with V_f of 15 V. Thus, a preferable electron emission characteristic can be obtained with a small fluctuation of I_e with time.

On the other hand, I_f is similar to the characteristic of I_e , and the value is smaller than the value of I_e by one digit.

The mechanism of the equalizing process according to the present embodiment is described below by referring to FIG. 13. FIG. 13 shows a change in device characteristic before and after the equalizing process.

The electron-emitting device before the equalizing process shows the characteristic of emitting an

electron at the threshold V_{th1} (about 1 V/ μ m). Then, as described above, when a pulse voltage is applied to the device in the O_2 gas, the electron emission current of the device is suddenly reduced by the mechanism of the chemical etching of the above mentioned carbon. The voltage applied to the device is gradually increased, and the process is performed until no emission is emitted at the threshold voltage of V_{th2} .

When the device characteristic is evaluated after evacuating the O_2 gas, the characteristic has been changed such that an electron is emitted at the threshold of V_{th2} . At this time, it is assumed that the fluctuation width of the electron emission current obtained by the electron emission has been reduced, and the number of electron emission points has increased in the equalizing process.

The diameter of an electron beam emitted from the device obtained according to the present embodiment is long in the Y direction and short in the X direction, that is, substantially rectangular.

(Second Embodiment)

An example of the equalizing process performed by emitting an electron as biased between the cathode electrode of the electron-emitting device and the anode opposing the electron-emitting device in the O_2 gas in the second embodiment.

(Step 1)

In the method similarly used in the steps 1 to 4 according to the first embodiment, the extraction electrode 2 and the cathode electrode 3 are formed on the substrate 1, and fibrous carbon is produced as the
5 electron-emitting member 4 on the substrate 1.

(Step 2)

The electron-emitting device is provided for the vacuum device 20 as shown in FIGS. 2A and 2B, the evacuation device 23 performs the evacuation process
10 until 2×10^{-6} Pa is reached, the gas leading valve 22 leads the O_2 gas until the vacuum level in the vacuum device 20 reaches 1×10^{-4} Pa, and the pulse voltage of $V_f = 20$ V (with the pulse width of 10 msec and the pulse length of 4 msec) is applied to the cathode
15 electrode 3 of the electron-emitting device with the extraction electrode 2 of the electron-emitting device set positive. Simultaneously, a voltage of $V_a = 10$ kV is applied to the anode 24. The system is operated in this state for 1 hour, and the electron-emitting member
20 4 is equalized.

The electron-emitting device produced as mentioned above is fixed to the V_r of 15 V, the inter-anode distance H is fixed to 2 mm, and the device is driven with the anode voltage V_a of 10 kV. With the
25 configuration, a stable I_e can be obtained as in the first embodiment.

(Third Embodiment)

An example of the equalizing process performed for each line of a matrix in the display device comprising a matrix electron source in which a plurality of electron-emitting devices are provided is described
5 below by referring to FIGS. 8 and 9.

In FIG. 8, reference numeral 81 denotes an electron source substrate, reference numeral 82 is X direction wiring, and reference numeral 83 is Y direction wiring, reference numeral 84 denotes an
10 electron-emitting device, and reference numeral 85 denotes a connection line.

When the device capacity of a plurality of devices increases, the waveform becomes unclear by the capacity elements although a short pulse accompanied by the
15 pulse width modulation is added in the matrix wiring as shown in FIG. 8, and the problem that an expected gray scale cannot be obtained, etc. occurs.

Therefore, according to the present embodiment as in the first embodiment, an inter-layer insulation
20 layer is provided close to the electron-emitting member 4, thereby reducing the increase by the capacity element outside the element emission area.

In FIG. 8, the X direction wiring 82 comprises m pieces of wiring, that is, Dx1, Dx2, ..., Dx_m, and
25 comprises about 1 μ m thick and 300 μ m wide aluminum wiring material formed in the evaporation method. The material, thickness of film, and width of the wiring

are appropriately designed.

The Y direction wiring 83 comprises n pieces of wiring, that is, Dy_1 , Dy_2 , ..., Dy_n , and is 0.5 μm thick and 100 μm wide as similarly formed as the X direction wiring 82.

There is an inter-layer insulation layer not shown in the attached drawings between the m pieces of X direction wiring 82 and n pieces of Y direction wiring 83. They are electrically separated (m and n indicate positive integers).

The inter-layer insulation layer not shown in the attached drawings is configured by a 0.8 μm thick SiO_2 in the spatter method, etc. The thickness of the inter-layer insulation layer is determined such that it can be formed in a desired shape on all or a part of the substrate 81 forming the X direction wiring 82, specifically such that it is durable against the potential difference of the cross portion between the X direction wiring 82 and the Y direction wiring 83, that is, the device capacity per device is 1 pF or smaller, and the device durability of 30 V according to the present embodiment.

The X direction wiring 82 and the Y direction wiring 83 are lead as external terminals.

A pair of electrodes (not shown in the attached drawings) forming the electron-emitting device 84 electrically connected through m pieces of X direction

wiring 82, n pieces of Y direction wiring 83, and the connection line 85 comprising a conductive metal, etc.

According to the present embodiment, the Y direction wiring and the X direction wiring are
5 connected respectively as the cathode electrode side and the extraction electrode side.

The n pieces of Y direction wiring of Dyl, Dy2, ..., Dyn are commonly grounded, the pulse voltage on the positive side to the ground is applied to Dx1, the
10 electron-emitting device 84 of the row Dx1 is selected, and the equalizing process is performed.

Then, a similar voltage is applied to Dx2, the electron-emitting device 84 of the row Dx2 is selected, and the equalizing process is performed. Similarly,
15 the rows Dx3, Dx4, ..., Dxm are selected to perform the equalizing process sequentially in the X direction.

The image-forming apparatus configured using the electron source in the simple matrix array is described below by referring to FIG. 9. FIG. 9 shows the display
20 panel of the image-forming apparatus using soda lime glass as a glass substrate material.

In FIG. 9, reference numeral 81 denotes an electron source substrate for which a plurality of electron-emitting devices are provided, reference
25 numeral 91 denotes a rear plate to which the electron source substrate 81 is fixed, and reference numeral 96 denotes a face plate in which the fluorescent film 94,

the metal back 95, etc. are formed inside the glass substrate 93. Reference numeral 92 denotes a support frame to which the rear plate 91 and the face plate 96 are connected using frit glass, etc. Reference numeral
5 97 denotes an envelope which is sealed by baking at the temperature of 450°C in the vacuum for ten minutes.

Reference numeral 84 denotes an electron-emitting device. X direction wiring 82 and Y direction wiring 83 are connected to a pair of device electrodes of an
10 electron-emitting device. The respective row wiring and column wiring of the X direction wiring 82 and the Y direction wiring 83 are lead outside the envelope 97 as terminals of Dox1 to Doxm and Doy1 to Doy n.

The envelope 97 comprises the face plate 96, the
15 support frame 92, and the rear plate 91 as described above. In the other hand, the envelope 97 having sufficient strength against the atmosphere by providing a support referred to as a spacer, but not shown in the attached drawings between the face plate 96 and the
20 rear plate 91.

The metal back 95 performs a smoothing process (normally referred to as a "filming") on the inner surface of the fluorescent film 94 after producing the fluorescent film 94, and then the vacuum evaporation
25 process, etc. is performed, thereby piling Al.

To enhance the conductivity of the fluorescent film 94, the face plate 96 is provided with a

transparent electrode (not shown in the attached drawings) outside the fluorescent film 94.

Since the electron from the electron source is emitted to the extraction electrode 2 side according to the present embodiment, the fluorescent film 94 is provided in the position 200 μm shifted toward the extraction electrode 2 when the anode voltage V_a is 10 kV and the inter-anode distance H is 2 mm.

Thus, the obtained matrix electron source indicates equal characteristic for each electron-emitting device 84, and indicates little distribution of I_e , therefore it is desired as a display device, etc.

(Fourth Embodiment)

According to the present embodiment, an example of an equalizing process is performed for each electron-emitting device in the display device as an image-forming apparatus comprising a matrix electron source for which a plurality of electron-emitting devices are provided.

As in the third embodiment, the matrix electron source as shown in FIG. 8 is produced. According to the present embodiment, the Y direction wiring 83 is connected to the cathode electrode, and the X direction wiring 82 is connected to the extraction electrode.

A voltage is applied to D_{y1} and D_{x1} , the electron-emitting device 84 at the cross portion between D_{y1} and

Dx1 is selected, and it is independently driven and the equalizing process is performed.

Then, a similar voltage is applied to Dyl and Dx2, the electron-emitting device 84 at the cross portion
5 between Dyl and Dx2 is independently selected, and the equalizing process is performed. Similarly, the equalizing process is performed sequentially on each of the electron-emitting devices 84.

Using the matrix electron source produced
10 according to the present embodiment, the display device as shown in FIG. 9 is produced as in the third embodiment.

With the matrix electron source obtained as described above, the distribution of I_e is further
15 reduced, and is recommended as a display device, etc.

As described above, according to the present invention, the shapes of a plurality of projections of the electron-emitting member 4 are equalized.
Therefore, a local field condensation is avoided on the
20 electron-emitting member, and the electron emission characteristic can be equalized. Additionally, the local field condensation which causes high current density and an overload can be suppressed, thereby avoiding the reduction of an emission current.

25 Therefore, the induction of discharge can be suppressed, the durability of the electron-emitting device can be elongated, and a stable electron emission

current with a small fluctuation with time can be maintained for a long period.

Furthermore, for an electron source and an image-forming apparatus provided with a plurality of
5 electron-emitting devices, the electron emission current of each electron-emitting device can be stably maintained. Therefore, the durability of each pixel can be elongated, the brightness of an image can be successfully represented, and the flicker of an image
10 can be avoided, thereby maintaining a constant display characteristic for a long period.

WHAT IS CLAIMED IS:

1. A method for producing an electron-emitting device, comprising the steps of:

5 (A) disposing a cathode electrode on a surface of a substrate;

(B) providing an electrode opposite the cathode electrode;

(C) disposing plural pieces of fiber containing carbon as a main component on the cathode electrode;
10 and

(D) applying potential higher than potential applied to the cathode electrode under depressurized condition to an electrode opposite the cathode electrode.
15

2. The method for producing an electron-emitting device, according to claim 1, wherein

said electrode opposite the cathode electrode is an anode electrode provided apart the substrate.
20

3. The method for producing an electron-emitting device, according to claim 1, wherein

said electrode opposite the cathode electrode is a leading electrode provided apart from the cathode
25 electrode on the surface of the substrate.

4. The method for producing an electron-emitting

device, according to claim 1, wherein

said step of applying potential to the electrode opposite the cathode electrode is a step of increasing the number of emission sites.

5

5. The method for producing an electron-emitting device, according to claim 1, wherein

said potential applied to the electrode opposite the cathode electrode is potential at which an electron is emitted from the fiber.

10

6. The method for producing an electron-emitting device, according to claim 1, wherein

said step of applying the potential to the electrode opposite the cathode electrode is performed under condition of a gas chemically or physically reactive to the fiber.

15

7. The method for producing an electron-emitting device, according to claim 6, wherein

20

said gas chemically reactive to the fiber is one of O₂, H₂, CO₂, and H₂O.

8. The method for producing an electron-emitting device, according to claim 6, wherein

25

a pressure for introducing the gas is equal to or over 1×10^{-4} Pa.

9. The method for producing an electron-emitting device, according to claim 6, wherein

said step of applying the potential to the electrode opposite the cathode electrode is a step of
5 applying a pulse voltage between the cathode electrode and the electrode opposite the cathode electrode.

10. The method for producing an electron-emitting device, according to claim 1, wherein

10 said fiber is formed by decomposing a hydrogen carbide gas.

11. The method for producing an electron-emitting device, according to claim 10, wherein

15 said fiber is formed by decomposing the hydrogen carbide gas using a catalyst provided on the cathode electrode in advance.

12. The method for producing an electron-emitting
20 device, according to claim 11, wherein

said catalyst is one of Fe, Co, Pd, and Ni, or an alloy consisting of materials selected from among Fe, Co, Pd, and Ni.

25 13. The method for producing an electron-emitting device, according to claim 1, wherein

said fiber is formed by graphite nanofiber, carbon

nanotube, or amorphous carbon fiber.

14. The method for producing an electron-emitting device, according to claim 1, wherein

5 said fiber comprises a graphen.

15. The method for producing an electron-emitting device, according to claim 1, wherein

10 said fiber comprises a plurality of graphens.

16. The method for producing an electron-emitting device, according to claim 15, wherein

15 said plurality of graphens are layered in an axial direction of the fiber.

17. A method for producing an electron source obtained by arranging a plurality of electron-emitting devices, which are produced according to any of claims 1 to 16.

20

18. A method for producing an image-forming apparatus having an electron source and an image-forming member, wherein

25 said electron source is produced in the method according to claim 17.

19. A method for producing an electron source

having a plurality of electron-emitting devices,
comprising the steps of:

(A) providing on a substrate a plurality of
electron-emitting devices comprising plural pieces of
5 fiber each containing carbon as a main component, and
plural pieces of wiring electrically connected to at
least one of the plurality of electron-emitting
devices;

(B) measuring by applying a voltage to at least a
10 part of the plurality of electron-emitting devices, an
electrical characteristic of said at least a part of
the plurality of electron-emitting devices to which the
voltage is applied;

(C) reducing a difference in electrical
15 characteristic among the plurality of electron-emitting
devices based on a measurement result, wherein

said step of reducing the difference in
characteristic among the plurality of electron-emitting
devices comprising a step of emitting an electron from
20 at least one of the plurality of electron-emitting
devices under depressurized condition.

20. The method for producing an electron source,
according to claim 19, wherein

25 said plural pieces of wiring comprises plural
pieces of row direction wiring, and plural pieces of
column direction wiring crossing the row direction

wiring, and each of the electron-emitting devices is connected to one of the row direction wiring and one of the column direction wiring.

5 21. The method for producing an electron source, according to claim 20, wherein
said step of reducing the difference in
characteristic among the plurality of electron-emitting
devices contains a step of emitting an electron from a
10 desired electron-emitting device by repeating a step of selecting from said plural pieces of column direction wiring or said plural piece of row direction wiring, a part of the pieces of column direction wiring or row direction wiring, and emitting an electron from an
15 electron-emitting device connected to the selected wiring.

22. The method for producing an electron source, according to claim 19, wherein
20 said step of reducing the difference in
characteristic among the plurality of electron-emitting devices contains a step of emitting an electron from a desired electron-emitting device by repeating a step of selecting a part of electron-emitting devices from
25 among the plurality of electron-emitting devices and emitting an electron from the selected electron-emitting device.

23. The method for producing an electron source,
according to claim 19, wherein:

5 said electron-emitting device contains a cathode
electrode to which the fiber is electrically connected,
and a leading electrode provided apart from the cathode
electrode; and

10 said step of emitting an electron from the
electron-emitting device is performed by applying a
voltage between the cathode electrode and the leading
electrode.

24. The method for producing an electron source,
according to claim 19, wherein

15 said step of emitting an electron from the
electron-emitting device is performed by applying a
voltage between the electrode provided apart from the
substrate and the electron-emitting device.

20 25. The method for producing an electron source,
according to claim 19, wherein:

 said electron-emitting device contains a cathode
electrode to which the fiber is electrically connected,
and a leading electrode provided apart from the cathode
electrode; and

25 said step of emitting an electron from the
electron-emitting device is performed by applying a
potential difference between an electrode provided

apart from the substrate and the electron-emitting device.

26. The method for producing an electron source,
5 according to claim 19, wherein

said step of reducing the difference in
characteristic among the plurality of electron-emitting
devices is a step of increasing the number of emission
sites of at least one electron-emitting device.

10

27. The method for producing an electron source,
according to claim 19, wherein

said step of reducing the difference in
characteristic among the plurality of electron-emitting
15 devices is performed in ambient of a gas chemically or
physically reactive to the fiber.

28. The method for producing an electron source,
according to claim 27, wherein

20 said gas chemically reactive to the fiber contains
a gas selected at least from among O₂, H₂, CO₂, and H₂O.

29. The method for producing an electron source,
according to claim 28, wherein

25 a pressure for introducing the gas is equal to or
over 1×10^{-4} Pa.

30. The method for producing an electron source,
according to claim 27, wherein

said step of emitting an electron from the
electron-emitting device is performed by applying a
5 pulse voltage to the electron-emitting device.

31. The method for producing an electron source,
according to claim 19, wherein

said fiber is formed by decomposing a hydrogen
10 carbide gas.

32. The method for producing an electron-emitting
device, according to claim 31, wherein

said fiber is formed by decomposing the hydrogen
15 carbide gas using a catalyst provided on the cathode
electrode in advance.

33. The method for producing an electron-emitting
device, according to claim 32, wherein

20 said catalyst is one of Fe, Co, Pd, and Ni, or an
alloy consisting of materials selected from among Fe,
Co, Pd, and Ni.

34. The method for producing an electron-emitting
25 device, according to claim 19, wherein

said fiber is formed by graphite nanofiber, carbon
nanotube, or amorphous carbon fiber.

35. The method for producing an electron-emitting device, according to claim 19, wherein said fiber comprises a graphen.

5 36. The method for producing an electron-emitting device, according to claim 19, wherein said fiber comprises a plurality of graphens.

10 37. An electron-emitting device according to claim 36, wherein said plurality of graphens are layered in an axial direction of the fiber containing carbon as a main component.

15 38. A method for producing an image-forming apparatus having an electron source and an electron-emitting member, wherein said electron source is produced in the method according to any of claims 19 to 37.

20 39. The method for producing an image-forming apparatus, according to claim 38, wherein said image-forming apparatus is obtained by seal bonding a first substrate provided with the image-forming member with a second substrate provided with the electron source; and an electrical characteristic of the electron-emitting device is measured before the

25

first and second substrates are seal bonded with each other.

40. The method for producing an image-forming
5 apparatus, according to claim 38, wherein
said image-forming apparatus is obtained by seal
bonding a first substrate provided with the image-
forming member with a second substrate provided with
the electron source; and said step of reducing the
10 difference in electrical characteristic among the
plurality of electron-emitting devices is performed
before the first and second substrates are seal bonded
with each other.

ABSTRACT OF THE DISCLOSURE

A method for producing a durable electron-emitting device having a uniform electron emission characteristic, an electron source, and an image-forming apparatus having a uniform display characteristic for a long period are provided. The method for producing an electron-emitting device according to the present invention includes the steps of: disposing a cathode electrode on a surface of a substrate; providing an electrode opposite the cathode electrode; disposing plural pieces of fiber containing carbon as a main component on the cathode electrode; and applying potential higher than potential applied to the cathode electrode under depressurized condition to an electrode opposite the cathode electrode.

FIG. 1A

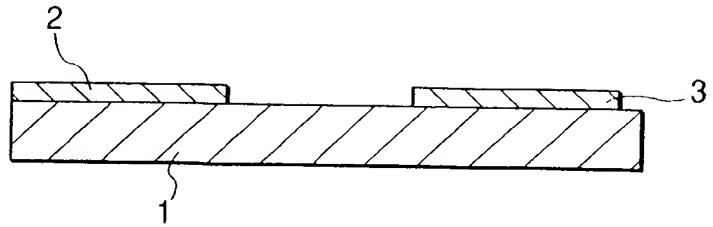


FIG. 1B

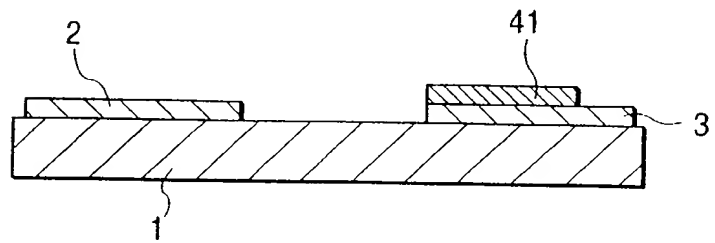


FIG. 1C

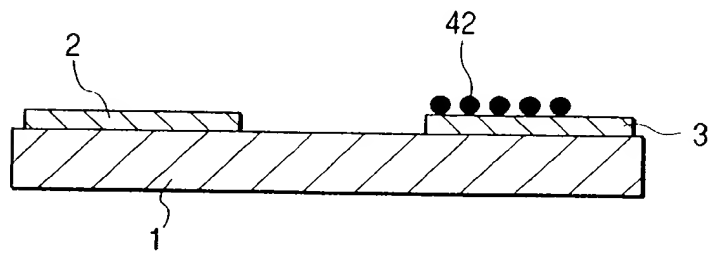


FIG. 1D

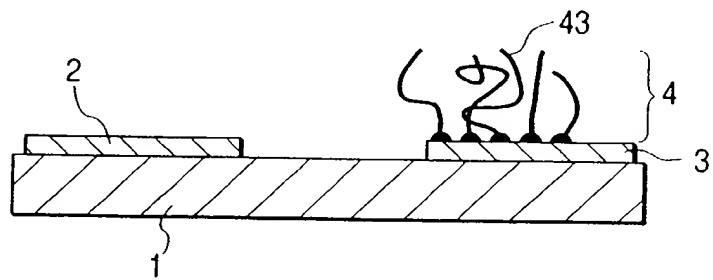


FIG. 1E

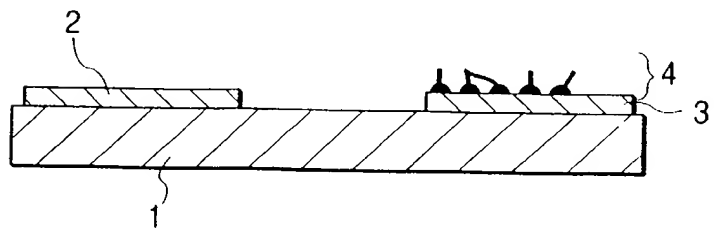


FIG. 2A

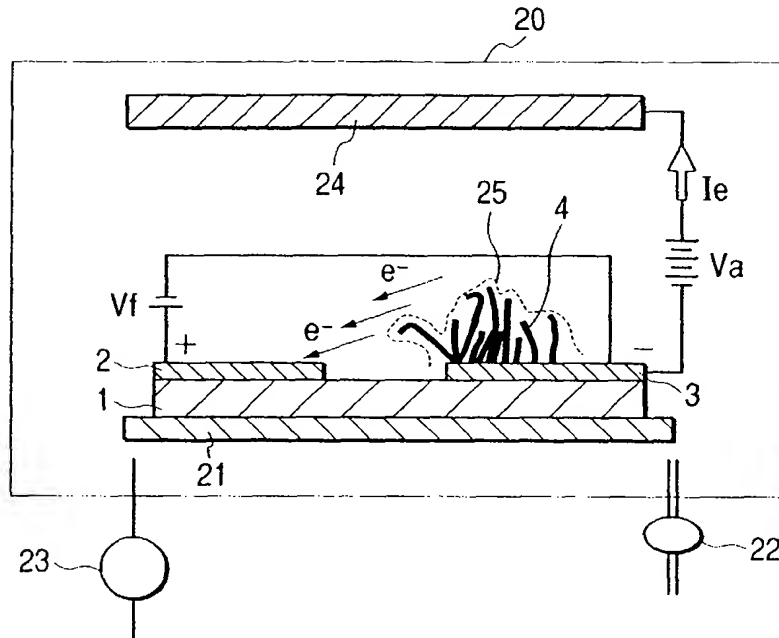


FIG. 2B

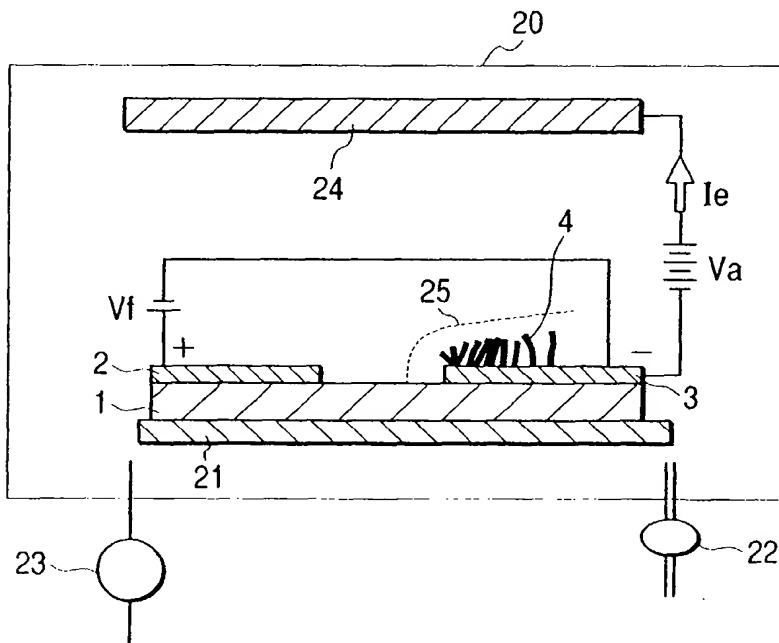


FIG. 3A

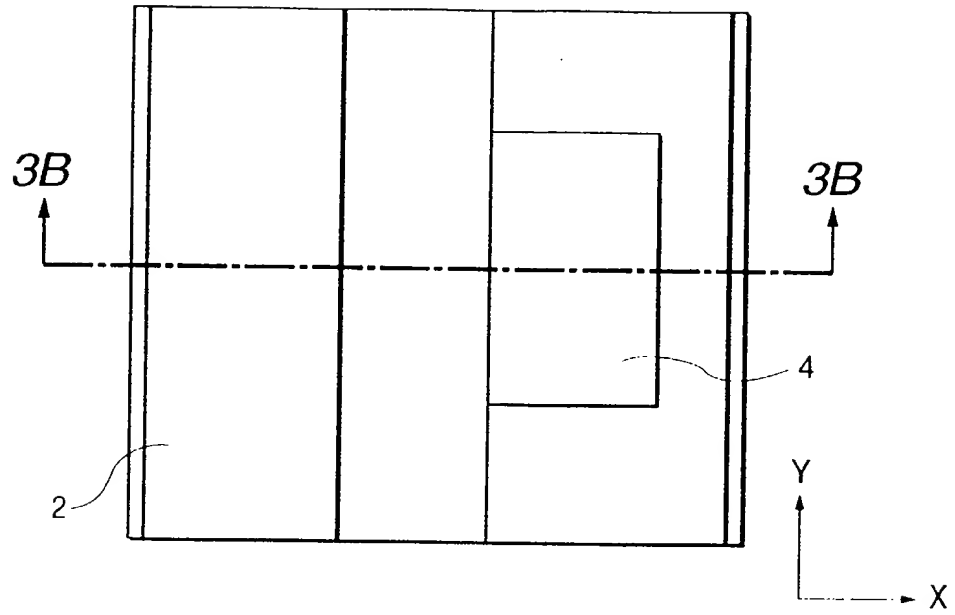


FIG. 3B

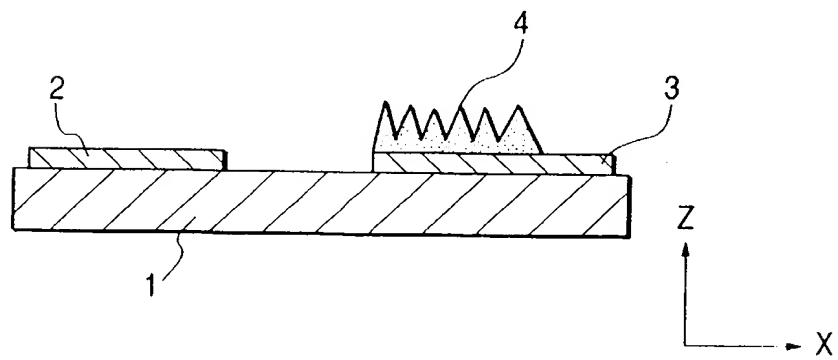


FIG. 4A

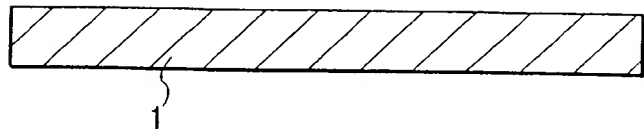


FIG. 4B

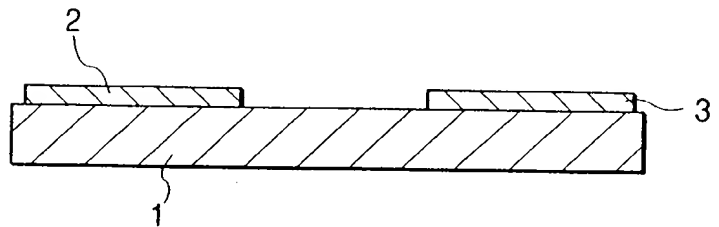


FIG. 4C

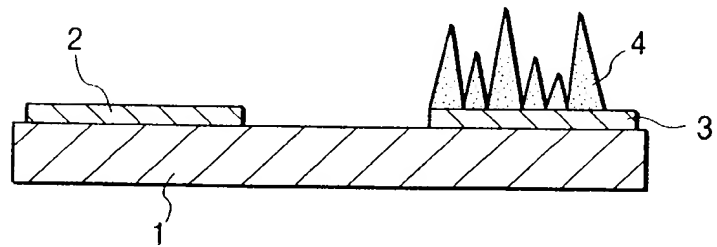


FIG. 4D

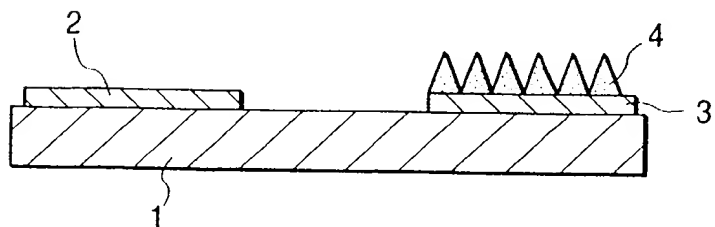


FIG. 5A

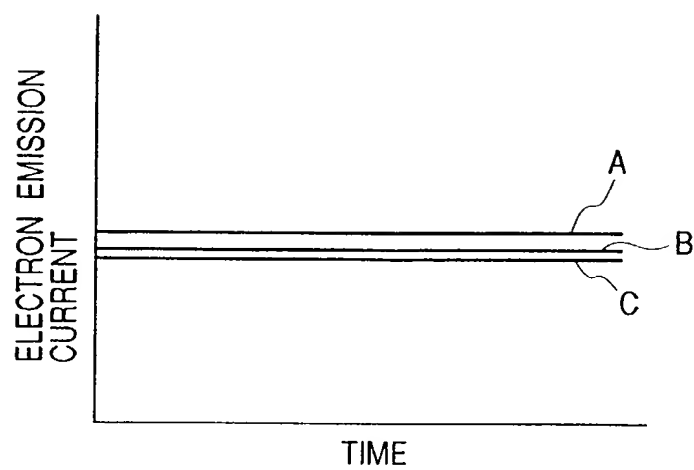


FIG. 5B

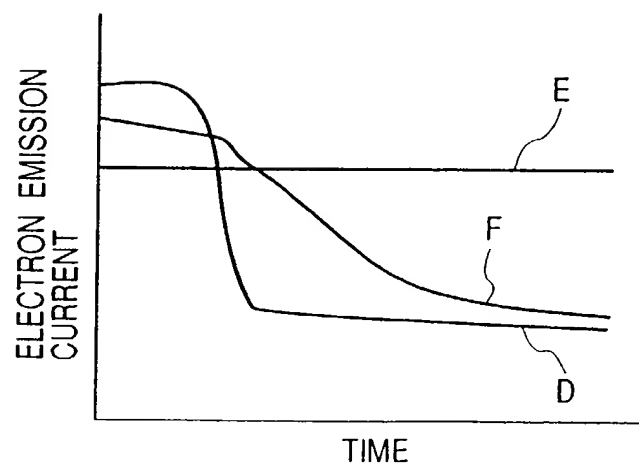


FIG. 6

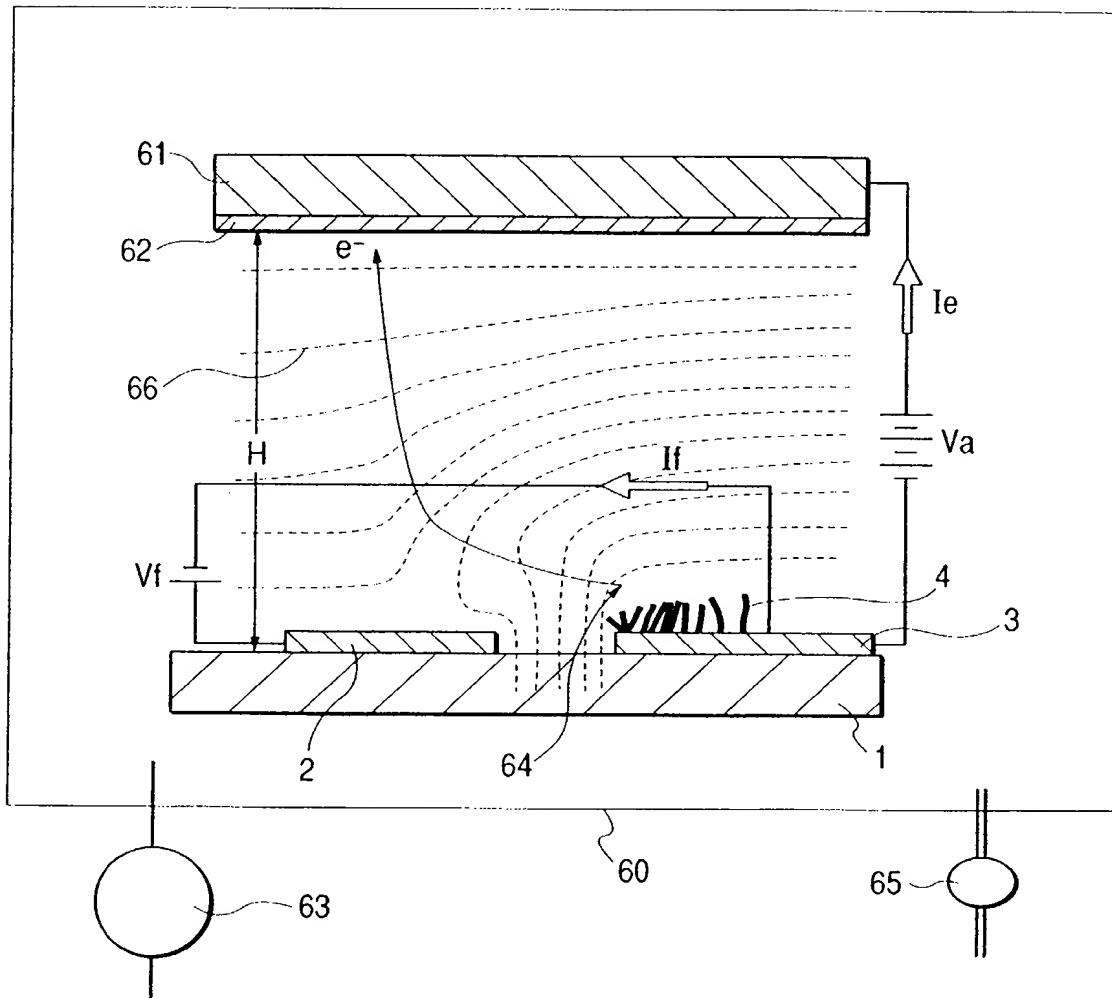


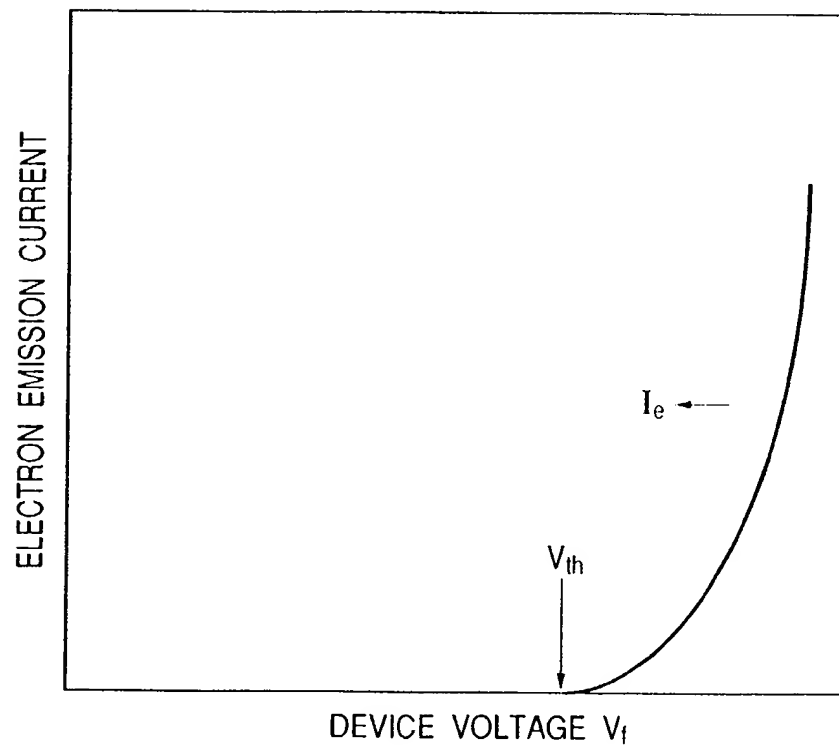
FIG. 7

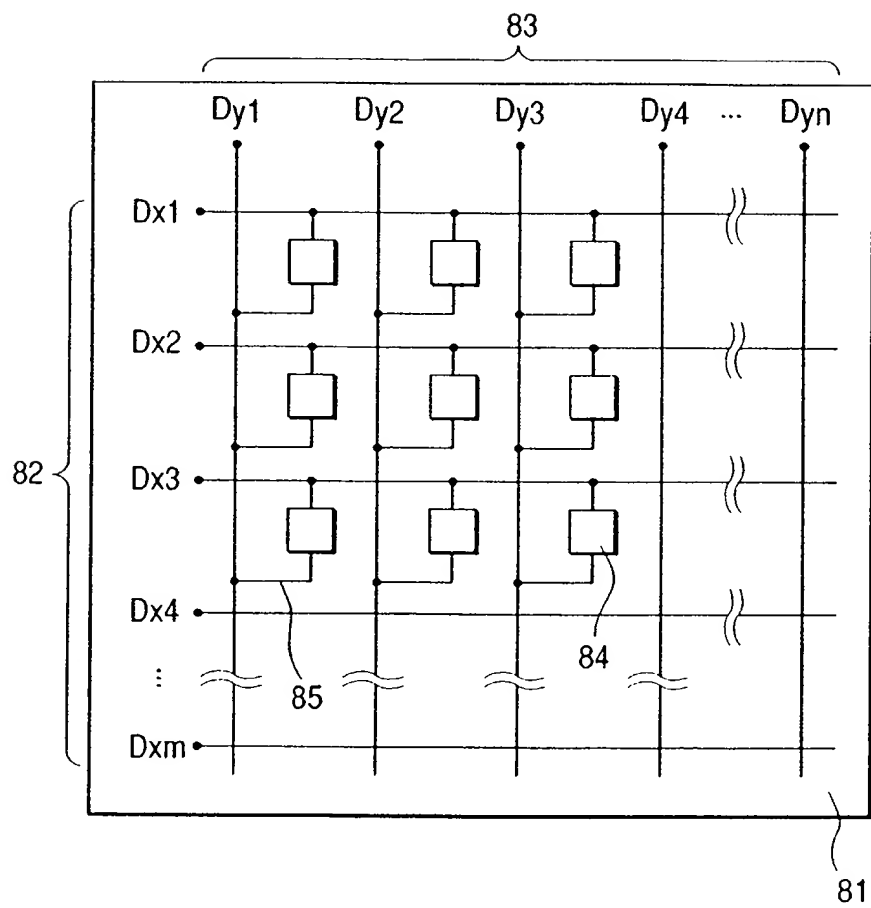
FIG. 8

FIG. 9

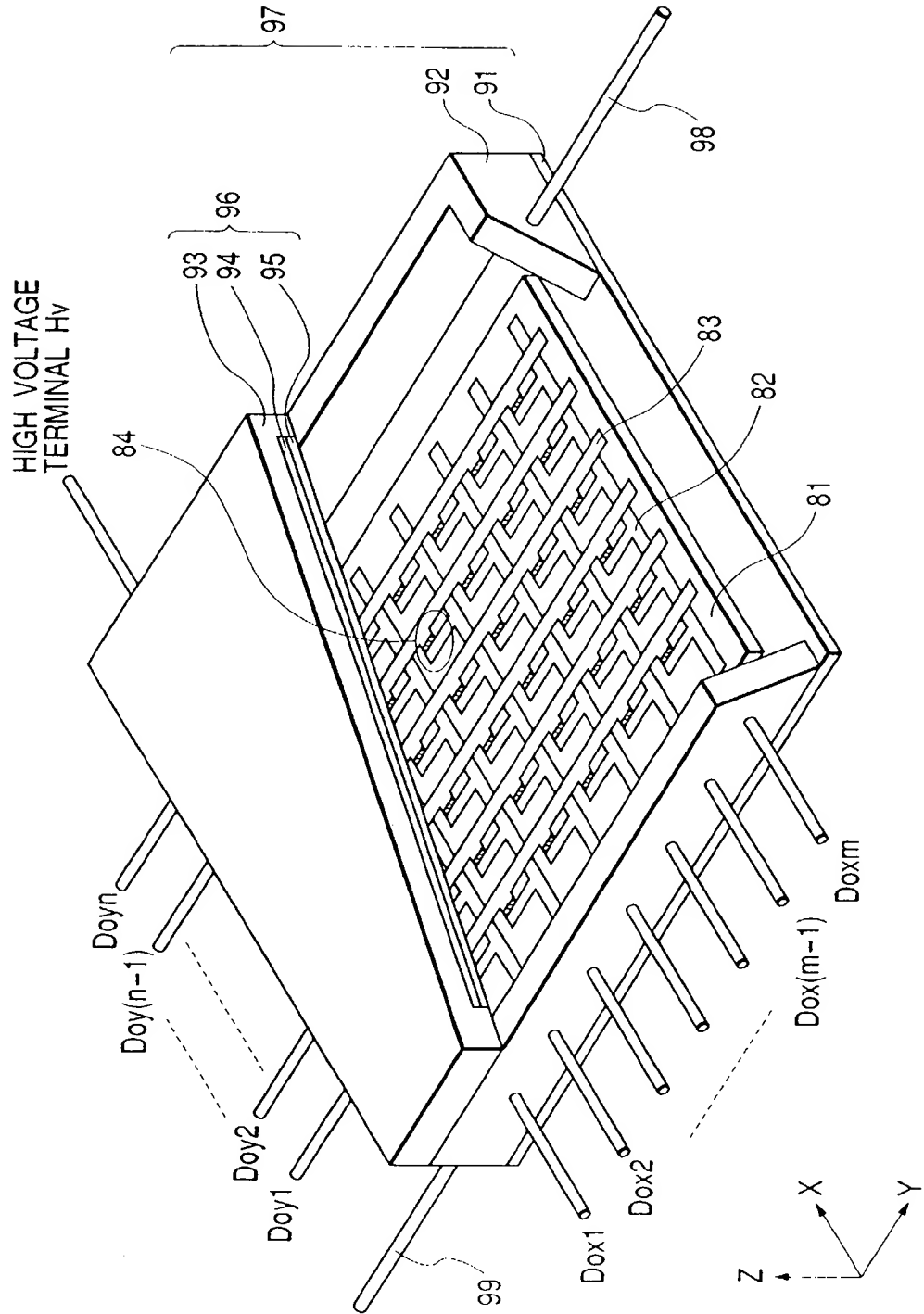


FIG. 10

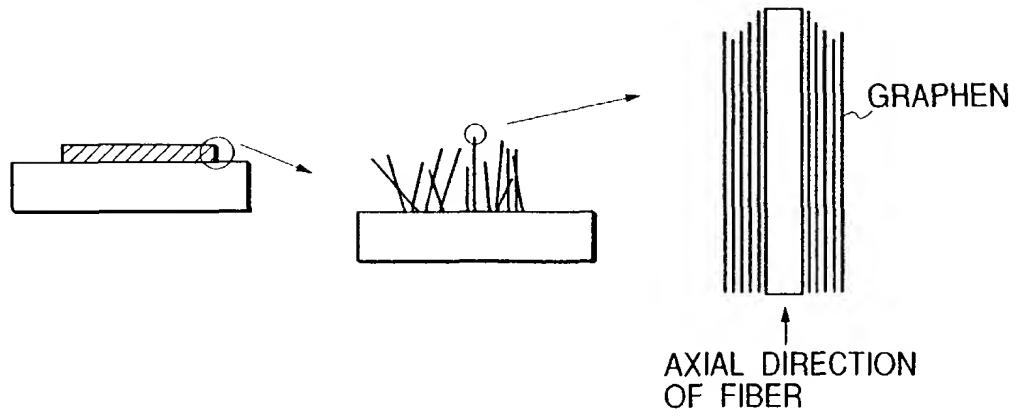


FIG. 11

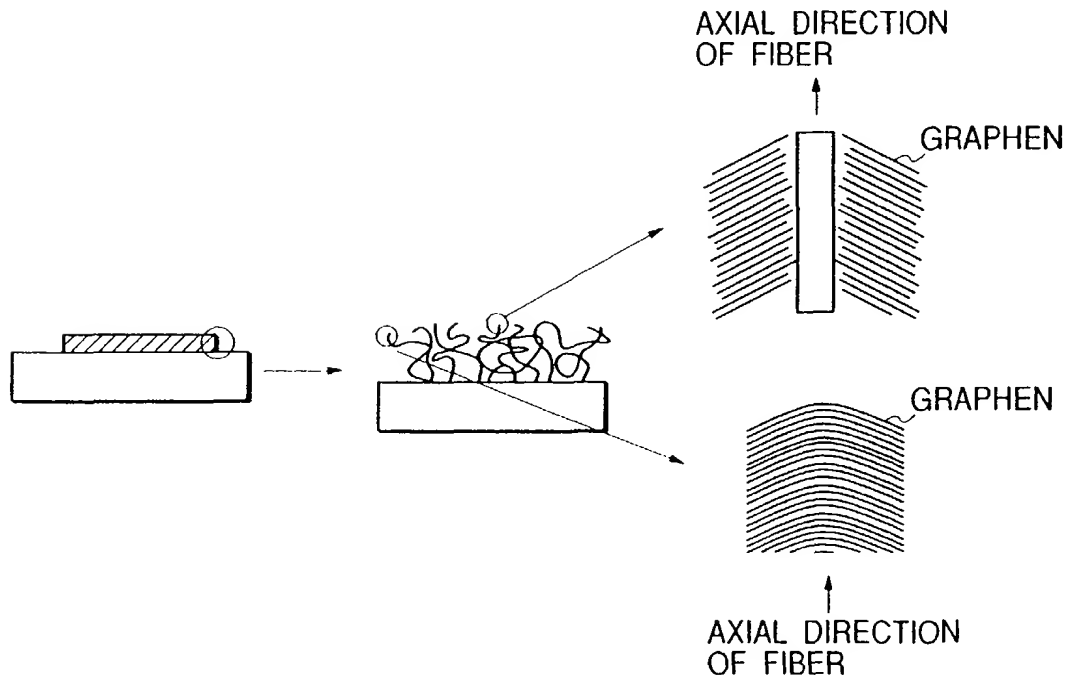


FIG. 12

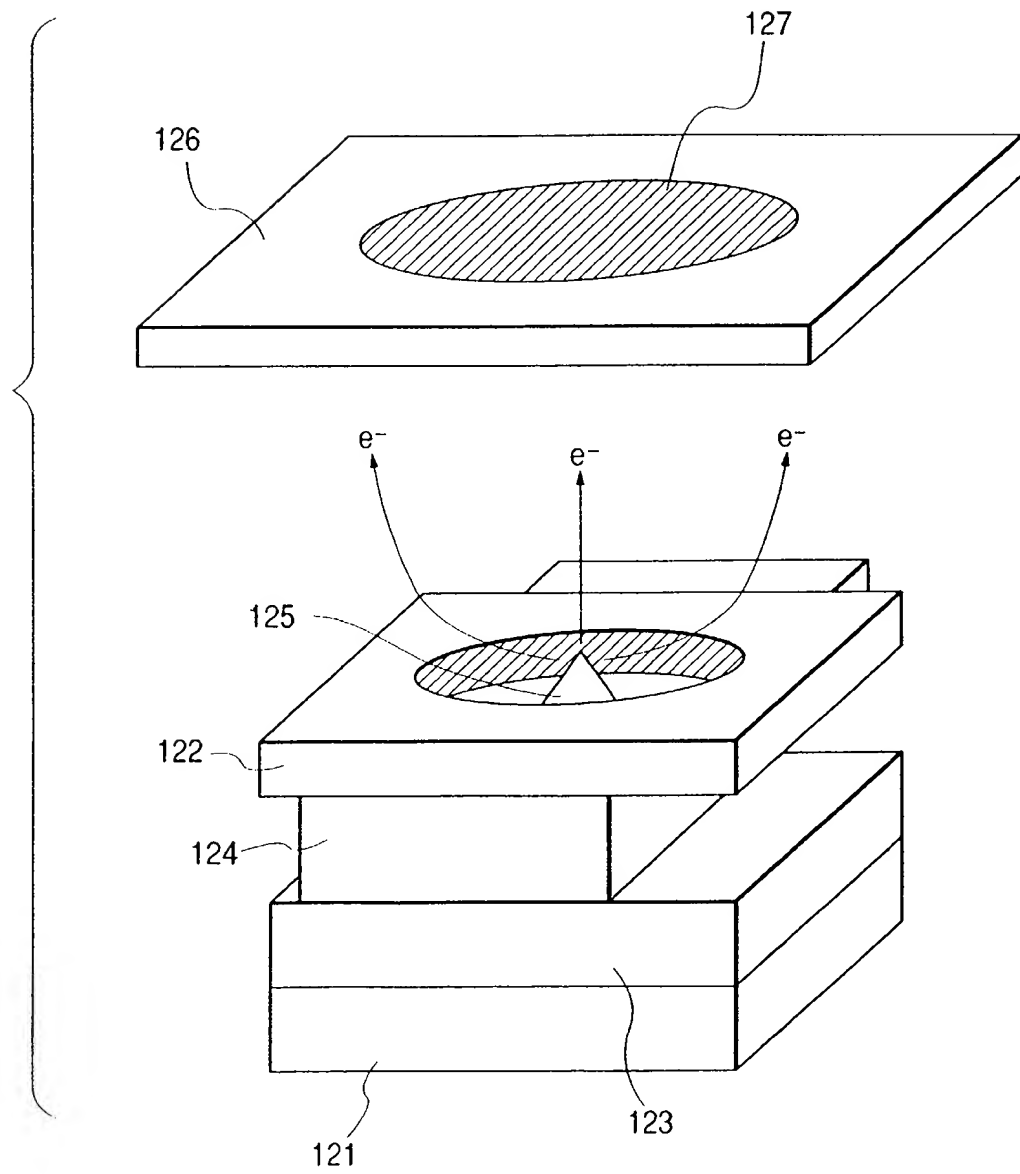
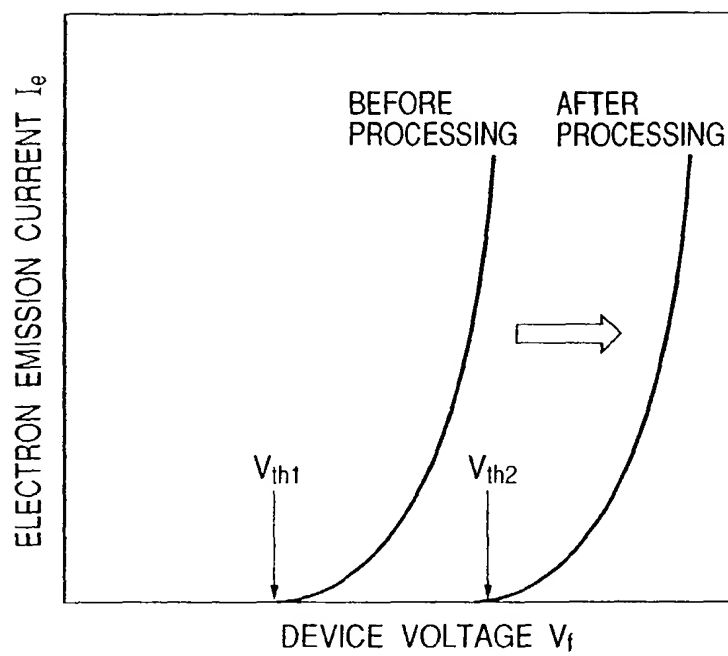
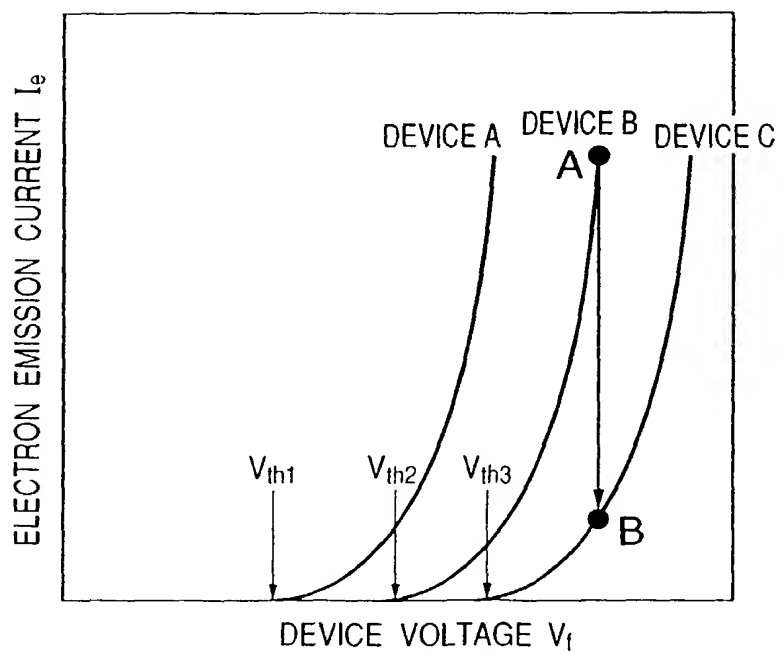


FIG. 13**FIG. 14**

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- 1 -



- 1 Method of Manufacturing Electron-emitting Device
as well as Electron Source and Image-forming Apparatus

BACKGROUND OF THE INVENTION

- 5 Field of the Invention

This invention relates to a method of manufacturing an electron-emitting device and it also relates to an electron source and an image-forming apparatus such as a display apparatus incorporating an electron-emitting device manufactured by such a method.

Related Background Art

There have been known two types of electron-emitting device; the thermoelectron type and the cold cathode type. Of these, the cold cathode type include the field emission type (hereinafter referred to as the FE-type), the metal/insulation layer/metal type (hereinafter referred to as the MIM-type) and the surface conduction type.

Examples of the FE electron-emitting device are described in W. P. Dyke & W. W. Dolan, "Field emission", Advance in Electron Physics, 8, 89 (1956) and C. A. Spindt, "PHYSICAL Properties of thin-film field emission cathodes with molybdenum cones", J. Appl. Phys., 47, 5248 (1976).

25 MIM devices are disclosed in papers including C. A. Mead, "The tunnel-emission amplifier", J. Appl. Phys., 32, 646 (1961).

1 Surface conduction electron-emitting devices
are proposed in papers including M. I. Elinson, Radio
Eng. Electron Phys., 10 (1965).

 A surface conduction electron-emitting device
5 is realized by utilizing the phenomenon that electrons
are emitted out of a small thin film formed on a substrate
when an electric current is forced to flow in parallel
with the film surface. While Elinson proposes the use of
SnO₂ thin film for a device of this type, the use of Au
10 thin film is proposed in G. Dittmer: "Thin Solid Films",
9, 317 (1972) whereas the use of In₂O₃/SnO₂ and that of
carbon thin film are discussed respectively in M. Hartwell
and C. G. Fonstad: "IEEE Trans. ED Conf.", 519 (1975) and
in H. Araki et al.: "Vacuum", Vol. 26, No. 1, p.22 (1983).

15 Fig. 24 of the accompanying drawings schematically
illustrates a typical surface conduction electron-
emitting device proposed by M. Hartwell.

 In Fig. 24, reference numeral 221 denotes a
substrate. Reference numeral 224 denotes an electro-
20 conductive film normally prepared as integrally with a
pair of device electrodes 225, 226 by producing an H-
shaped metal oxide thin film by means of sputtering,
part of which eventually makes an electron-emitting
region 223 when it is subjected to an electrically
25 energizing process referred to as "electric forming"
as described hereinafter. In Fig. 24, the horizontal
area of the metal oxide thin film separating the

1 pair of device electrodes 225, 226 has a length L of
0.5 to 1.0 mm and a width W of 0.1 mm. Note that the
electron-emitting region 223 is only very schematically
shown because there is no way to accurately know its
5 location and contour.

As described above, the electroconductive film
224 of such a surface conduction electron-emitting
device is normally subjected to an electrically
energizing preliminary process, which is referred to
10 as "electric forming", to produce an electron emitting
region 223.

In the electric forming process, a DC voltage
or a slowly rising voltage that rises typically at a
rate of 1V/min. is applied to given opposite ends of
15 the electroconductive film 224 to partly destroy,
deform or transform the thin film and produce an
electron-emitting region 223 which is electrically
highly resistive. Thus, the electron-emitting region
223 is part of the electroconductive film 224 that
20 typically contains fissures therein so that electrons
may be emitted from those fissures. Note that, once
subjected to an electric forming process, a surface
conduction electron-emitting device comes to emit
electrons from its electron emitting region 223
25 whenever an appropriate voltage is applied to the
electroconductive film 224 to make an electric current
run through the device.

1 Since a surface conduction electron-emitting
device as described above is structurally simple and
can be manufactured in a simple manner, a large number
of such devices can advantageously be arranged on a
5 large area without difficulty. As a matter of fact,
a number of studies have been made to fully exploit
this advantage of surface conduction electron-emitting
devices. Applications of devices of the type under
consideration include charged electron beam sources
10 and electronic displays.

 In typical examples of application involving a
large number of surface conduction electron-emitting
devices, the devices are arranged in parallel rows to
show a ladder-like shape and each of the devices are
15 respectively connected at given opposite ends with
wirings (common wirings) that are arranged in columns
to form an electron source (as disclosed in Japanese
Patent Application Laid-open Nos. 64-31332, 1-283749
and 1-257552).

20 As for display apparatuses and other image-
forming apparatuses comprising surface conduction
electron-emitting devices such as electronic displays,
although flat-panel type displays comprising a liquid
crystal panel in place of a CRT have gained popularity
25 in recent years, such displays are not without
problems. One of the problems is that a light source
needs to be additionally incorporated into the display

1 in order to illuminate the liquid crystal panel
because the display is not of the so-called emission
type and, therefore, the development of emission type
display apparatuses has been eagerly expected in the
5 industry.

An emission type electronic display that is
free from this problem can be realized by using an
electron source prepared by arranging a large number
of surface conduction electron-emitting devices in
10 combination with fluorescent bodies that are made to
shed visible light by electrons emitted from the
electron source (See, for example, United States Patent
No. 5,066,883).

For a surface conduction electron-emitting
15 device of the above described type, the electro-
conductive film is desirably made of a metal oxide
having an electric resistance sufficiently greater than
that of a metal film as in the case of the above
described M. Hartwell's electroconductive film 224
20 (Fig. 24). This is because a large electric current
is required for the electric forming operation if the
electroconductive film 224 has a low electric
resistance when the electron-emitting region is
produced by electric forming. The required electric
25 current will be huge and beyond any practical level
particularly when a large number of surface conduction
electron-emitting devices need to be simultaneously

1 subjected to an electric forming operation in the
process of manufacturing an electron source comprising
a plurality of surface conduction electron-emitting
devices.

5 On the other hand, an electron source comprising
a plurality of surface conduction electron-emitting
devices and an image-forming apparatus incorporating
such an electron source can be driven only by consuming
electric power at an enhanced rate if the electro-
10 conductive film of each device has a high electric
resistance.

SUMMARY OF THE INVENTION

In view of the above identified technological
15 problems, it is therefore an object of the present
invention to provide a method of manufacturing an
electron-emitting device that can effectively reduce
the drive voltage and the power consumption level of
the device.

20 Another object of the invention is to provide
an electron source and an image-forming apparatus that
operate on a power saving basis.

Still another object of the invention is to
provide an electron source comprising a plurality of
25 electron-emitting devices that operate uniformly for
electron emission and an image-forming apparatus
incorporating such an electron source and capable of

1 displaying high quality images.

A further object of the present invention is to provide a method of manufacturing an electron-emitting device that can effectively reduce the electric current for electric forming and the power consumption level required for driving the device as well as an energy saving electron source comprising a plurality of such electron-emitting devices that operate uniformly for electron emission and an image-forming apparatus incorporating such an electron source and capable of displaying high quality images.

According to a first aspect of the invention, the above objects and other objects of the invention are achieved by providing a method of manufacturing an electron-emitting device comprising a pair of oppositely disposed electrodes and an electroconductive film inclusive of an electron-emitting region arranged between said electrodes characterized in that said method comprises a processing step of reducing the electric resistance of the electroconductive film arranged between the electrodes.

Preferably, said processing step of reducing the electric resistance of the electroconductive film arranged between the electrodes is a step of chemically reducing the electroconductive film.

According to a second aspect of the invention, there is provided an electron source comprising an

1 electron-emitting device for emitting electrons as a
function of input signals characterized in that said
electron-emitting devices are produced by said manu-
facturing method.

5 According to a third aspect of the invention,
there is provided an image-forming apparatus comprising
an electron source and an image-forming member for
forming images as a function of input signals character-
ized in that said electron source is an electron source
10 comprising an electron-emitting device produced by
said manufacturing method.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A shows a schematic plan view of a
15 surface conduction electron-emitting device produced
by a manufacturing method according to the invention
and Fig. 1B shows an equivalent circuit for driving
the device.

Fig. 2 is a graph showing the relationships
20 between the device current and the device voltage and
between the emission current and the device voltage
before and after the chemical reduction step of an
electron-emitting device being produced by a manu-
facturing method according to the invention.

25 Figs. 3A to 3C show schematic sectional views
of an electron-emitting device in different steps of
manufacturing by a method according to the invention.

1 Fig. 4 is a schematic diagram showing the
configuration of a measuring system for determining
the performance of an electron-emitting device.

 Figs. 5A and 5B show forming voltage waveforms
5 that can suitably be used for the purpose of the present
invention.

 Fig. 6 is a graph showing a typical relation-
ships between the emission current I_e and the device
voltage V_f and between the device current I_f and the
10 device voltage V_f of a surface conduction electron-
emitting device produced by a manufacturing method
according to the invention.

 Figs. 7A and 7B schematically show a plan view
and a sectional view, respectively, of a surface
15 conduction electron-emitting device produced by a
manufacturing method according to the invention.

 Fig. 8 schematically shows a sectional view of
a surface conduction electron-emitting device of a
type different from that of the device of Figs. 7A and
20 7B produced by a manufacturing method according to the
invention.

 Fig. 9 is a schematic plan view of an electron
source having a simple matrix arrangement of electron-
emitting devices.

25 Fig. 10 is a schematic perspective view of the
display panel of an image-forming apparatus comprising
an electron source having a simple matrix arrangement

1 of electron-emitting devices.

Figs. 11A and 11B show two alternative fluorescent films that can be used for the purpose of the invention.

5 Fig. 12 is a block diagram of the drive circuit of an image-forming apparatus according to the invention adapted for the NTSC system.

Figs. 13A and 13B schematically show two alternative ladder-like arrangements of electron-emitting devices for an electron source according to the invention.

Fig. 14 is a schematic perspective view of the display panel of an image-forming apparatus according to the invention incorporating an electron source having a ladder-like arrangement of electron-emitting devices.

Fig. 15 is an enlarged schematic partial view of an electron source having a simple matrix arrangement of electron-emitting devices.

20 Fig. 16 is a schematic sectional view of an electron-emitting device of the electron source of Fig. 15 taken along line A-A'.

Figs. 17A to 17F and 18G to 18I show schematic sectional views of an electron-emitting device to be used for an electron source having a simple matrix arrangement, showing different manufacturing steps.

Fig. 19 is a schematic illustration of the

1 chemical reduction step of a method of manufacturing
an electron-emitting device according to the invention,
using a reducing gas.

Fig. 20 is a schematic sectional view of an
5 electron-emitting device according to the invention
after it is covered by a protective film.

Fig. 21 is a schematic illustration of the
chemical reduction step of a method of manufacturing
an electron-emitting device according to the invention
10 and conducted in a reducing solution.

Fig. 22 is a block diagram of the drive circuit
of an image-forming apparatus according to the invention
adapted for the NTSC system obtained by modifying that
of Fig. 12.

15 Fig. 23 is a block diagram of a display
apparatus realized by using an image-forming apparatus
according to the invention.

Fig. 24 is a schematic plan view of a
conventional surface conduction electron-emitting
20 device.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Now, the present invention will be described in
greater detail by referring to the accompanying drawings.

25 According to an aspect of the invention, there
is provided a method of manufacturing an electron-
emitting device comprising an electroconductive film

1 as a component thereof, wherein said method comprises
a processing step of reducing the electric resistance
of the electroconductive film so that the voltage to be
applied to and the power consumed by the electron-
5 emitting device may be significantly reduced.

The processing step of reducing the electric
resistance of the electroconductive film of an electron-
emitting device will be described by referring to Figs.,
1A, 1B and 2.

10 Fig. 1A shows a schematic plan view of a
surface conduction electron-emitting device produced
by a manufacturing method according to the invention
and comprising a pair of electrodes 5, 6 and an electro-
conductive film 4 inclusive of an electron-emitting
15 region 3 arranged between the electrodes. Note that
reference numeral 1 denotes an insulating substrate
and the electron-emitting region 3 contains fissures
to make itself electrically highly resistive.

When a certain voltage is applied to the electro-
20 conductive film 4 by an external power source via the
electrodes 5, 6 to cause an electric current to flow
therethrough, the electron-emitting region 3 emits
electrons.

Fig. 1B shows an equivalent circuit for driving
25 the electron-emitting device.

Referring to Fig. 1B, R_s and R_f respectively
denote the electric resistance of the electron-emitting

1 region 3 and that of each of the oppositely arranged
remaining portions of the electroconductive film 4.
While the oppositely disposed portions of the electro-
conductive film 4 other than the electron emitting
5 region 3 may have different values for electric
resistance from each other, it is assumed here for the
same of convenience that the electron emitting region
3 is arranged exactly in the middle between the
electrodes and the remaining portions of the electro-
10 conductive film 4 have electric resistances that are
equal to each other.

If the electric current required to cause the
electron-emitting device to emit electrons is i_d and
the voltage required to be applied to the device in
15 order to cause the current i_d to flow through the
device is V_f , the power consumption rate $P(\text{all})$ of the
electron-emitting device is expressed by equation
 $P(\text{all}) = V_f \cdot i_d$.

It should be noted here that $P(\text{all})$ include the
20 effective power consumption rate $P_s = R_s \cdot i_d^2$ that
represents the power consumed per unit time genuinely
by the electron emitting region in order to emit
electrons and the ineffective power consumption rate
 $P_f' = 2 \cdot R_f' \cdot i_d^2$ that represents the power consumed per
25 unit time by the remaining portions of the electro-
conductive film 4 that are connected in series to the
electron emitting region 3.

1 While the above description concerns a single
electron-emitting device, the overall ineffective power
consumption rate would become enormous for an electron
source comprising a plurality of such electron-
5 emitting devices and hence for an image-forming
apparatus incorporating such an electron source.

 The drive voltage and the power consumption
rate of the electron-emitting device can be reduced
by reducing the ineffective power consumption rate Pf' ,
10 that is, by making the electric resistance of the
portions of the electroconductive film 4 Rf' (herein-
after referred to as the electric resistance of the
electroconductive film 4) sufficiently small relative
to the electric resistance of the electron emitting
15 region 3 per se.

 If the electric resistance per unit square of
the electroconductive film 4 is $Ro\Omega$, then the
electric resistance of the electroconductive film 4 Rf'
is expressed by $Rf' = [L / (2 \cdot W)] \cdot Ro\Omega$. While Rf' can be
20 made smaller by reducing the distance L between the
electrodes 5 and 6 (hereinafter referred to as gas
length), a small value for L is not desirable because
it can seriously damage the flexibility with which the
entire electron-emitting device is to be designed.

25 More specifically, for an image-forming
apparatus having a large display screen, the distance
 L between the electrode 5 and 6 of each

1 electron-emitting device of the apparatus is preferably
not smaller than $3\mu\text{m}$ and more preferably not smaller
than tens of several μm from the view point of the
currently available level of performance of the
5 aligner, the accuracy of printing, the yield and
other manufacturing considerations for patterning the
electrodes.

In view of the above technological restrictions,
the present invention is intended to provide a method
10 of manufacturing a surface conduction electron-
emitting device comprising a pair of oppositely
disposed electrodes and an electroconductive film
inclusive of an electron-emitting region arranged
between said electrodes characterized in that said
15 method comprises a processing step of reducing the
electric resistance of the electroconductive film
arranged between the electrodes.

Preferably, said processing step of reducing
the electric resistance of the electroconductive film
20 arranged between the electrodes is a step of
chemically reducing the electroconductive film. With
such an operation of chemically reducing the electro-
conductive film 4, the ineffective power consumption
rate Pf' of the electroconductive film 4 can be
25 significantly reduced to allow electric power to be
effectively consumed for electron emission in the
device.

1 Now, the relationships between the device
current I_f and the device voltage V_f and between the
emission current I_e and the device voltage V_f before
and after the chemical reduction step of an electron-
5 emitting device being produced by a manufacturing
method according to the invention will be described
schematically by referring to Fig. 2. In Fig. 2, the
device current and the emission current before
chemical reduction are respectively indicated by I_{fo}
10 and I_{eo} whereas those after chemical reduction are
respectively denoted by I_{fm} and I_{em} .

As clearly seen from Fig. 2, both I_{fo} and I_{eo}
before chemical reduction are smaller than their
respective counter-parts I_{fm} and I_{em} after chemical
15 reduction. This means that almost all the device
voltage V_f applied to the electron-emitting device is
applied to the electron emitting region after the
operation of chemical reduction, whereas the device
voltage V_f is significantly lowered by the resistance
20 of the electroconductive film and only a fraction of
the device voltage V_f is actually applied to the
electron emitting region before the chemical reductions
step. In other words, a higher device voltage needs
to be applied to the electron-emitting device before
25 the chemical reduction step in order to compensate
the loss in the electroconductive film if an emission
current level equal to the level after the chemical

1 reduction step is to be achieved before the chemical
reduction step in the electron-emitting device. Then,
electric power will be consumed by the electro-
conductive film at an even higher rate.

5 Thus, according to the invention, the power
consumption rate of an electron-emitting device can
be reduced by chemically reducing the electroconductive
film. Preferable techniques for chemically reducing
the electroconductive film for the purpose of the
10 present invention include 1) heating the film in
vacuum, 2) keeping the film in an reducing atmosphere
and 3) keeping the film in a reducing solution. With
any of these techniques, the operation of chemically
reducing the electroconductive film is conducted,
15 while monitoring the electric resistance of the
electroconductive film, until the resistance gets to
a stable level and does not become lower any further.

Now, the best mode of carrying out the
invention will be described.

20 Firstly, a method of manufacturing a surface
conduction electron-emitting device according to the
invention will be described by referring to Figs. 3A-3C
that show a surface conduction electron-emitting device
in three different manufacturing steps.

25 A method of manufacturing a surface conduction
electron-emitting device according to the invention
comprises the following steps.

- 1 (A) Steps upto electric forming: the electroconductive
film arranged between a pair of electrodes on a
substrate is subjected to an electric forming operation.
- 1) After thoroughly cleansing a substrate 1 with
5 detergent and pure water, a material is deposited on
the substrate 1 by means of vacuum deposition,
sputtering or some other appropriate technique for a
pair of device electrodes 5 and 6, which are then
produced by photolithography (Fig. 3A).
- 10 2) An organic metal thin film is formed on the
substrate 1 between the pair of device electrodes 5
and 6 by applying an organic metal solution and
leaving the applied solution for a given period of
time. Thereafter, the organic metal thin film is
15 heated in an oxidizing atmosphere, for instance, in
the ambient air atmosphere and is charged to an
electroconductive film which comprises mainly metal
oxides and subsequently subjected to a patterning
operation, using an appropriate technique such as
20 lift-off or etching, to produce a thin film 2 for
forming an electron-emitting region (Fig. 3B). While
an organic metal solution is used to produce a thin
film in the above description, a thin film may
alternatively be formed by vacuum deposition,
25 sputtering, chemical vapor phase deposition, dispersed
application, dipping, spinner or some other technique.
- 3) Thereafter, the device is subjected to an electric

1 forming process.

In this electric forming operation, the electroconductive film 4 is locally destroyed, deformed or transformed such that a portion of the
5 electroconductive film 4 undergoes a structural change (to become a high electric resistance area) as fissures are formed there. Differently stated, a portion of the electroconductive film 4 undergoes a structural change to make an electron emitting region
10 3 in an electric forming process where a voltage is applied to the device electrodes 5 and 6 by a power source (not shown) to energize the electroconductive film 4 (Fig. 3C).

All the remaining steps of the electric
15 processing to be conducted on the device after the forming operation are carried out by using a measuring system which will be described below by referring to Fig. 4.

Referring to Fig. 4, the measuring system
20 comprises a power source 31 for applying a voltage to the device, an ammeter 30 for metering the device current I_f running through the electroconductive film 4 between the device electrodes, an anode 34 for capturing the emission current I_e emitted from the
25 electron-emitting region 3 of the device, a high voltage source 33 for applying a voltage to the anode 34 of the measuring system, another ammeter 32 for

1 metering the emission current I_e emitted from the
electron-emitting region 3 of the device, a vacuum
apparatus 35 and an exhaust pump 36. The exhaust pump
may be provided with an ordinary high vacuum system
5 comprising a turbo pump and a rotary pump or an oil-
free high vacuum system comprising an oil-free pump
such as a magnetic levitation turbo pump or a dry
pump and an ultra-high vacuum system comprising an
ion pump.

10 An electron-emitting device is placed in the
vacuum apparatus 35 for carrying out the remaining
steps of electric processing or for measuring the
performance of the device, which comprises a substrate
1, a pair of device electrodes 5 and 6 and an electro-
15 conductive film 4 including an electron emitting region
3 as shown in Fig. 4.

The vacuum apparatus 35 is provided with a
vacuum gauge and other pieces of equipment necessary
to operate it so that the measuring operation can be
20 conducted under a desired vacuum condition.

The vacuum chamber and the substrate of the
electron source can be heated to approximately 400°C
by means of a heater (not shown).

For determining the performance of the device,
25 a voltage between 1 and 10KV is applied to the anode,
which is spaced apart from the electron emitting device
by distance H which is between 2 and 8mm.

1 For the electric forming operation, a constant
pulse voltage or an increasing pulse voltage may be
applied. Figs. 5A and 5B show two possible electric
forming voltage waveforms.

5 For the purpose of the present invention, the
voltage to be applied to the device for an electric
forming operation preferably have a pulse waveform.
Fig. 5A shows a constant pulse waveform where the
pulse wave height is constant, whereas Fig. 5B shows an
10 increasing pulse waveform where the pulse wave height
increases with time.

Firstly, a voltage having a constant pulse wave
height will be described by referring to Fig. 5A.

Referring to Fig. 5A, the pulse voltage has a
15 pulse width T_1 and a pulse interval T_2 , which are
between 1 microsecond and 10 microseconds and between
10 microseconds and 100 milliseconds respectively.
The height of the triangular wave (the peak voltage for
the electric forming operation) may be appropriately
20 selected depending on the profile of the electron-
emitting device to be processed and the voltage is
applied for several seconds to several tens of minutes
under an appropriate vacuum conditions, for instance,
typically with a degree of vacuum of approximately
25 10^{-5} torr. Note that the pulse waveform to be applied
to the device electrodes is not limited to a triangular
waveform and may alternatively be a rectangular

1 waveform or some other appropriate waveform.

Secondly, a voltage having an increasing waveform will be described by referring to Fig. 5B.

Referring to Fig. 5B, the pulse voltage has a
5 width T1 and a pulse interval T2, which are between 1 microsecond and 10 microseconds and between 10 microseconds and 100 milliseconds respectively as in the case of Fig. 5A, although the height of the triangular wave (the peak voltage for the electric
10 forming operation) is increased at a rate of, for instance, 0.1V per step and the voltage is applied to the device in vacuum.

The electric forming operation will be terminated when typically a resistance greater than
15 1M ohms is observed for the device current If running through the electroconductive thin film 4 for forming an electron-emitting region while applying a resistance-measuring voltage of approximately 0.1V is applied to the device electrodes not to locally destroy or
20 deform the thin film.

(B) Reduction of electric resistance: the electroconductive film arranged between a pair of electrodes is subjected to a processing operation of reducing the electric resistance thereof.

25 4) The processing operation of reducing the electric resistance of the electroconductive film is an operation of chemically reducing the electroconductive

1 film.

The processing operation of chemically reducing the electroconductive film 4 including an electron-emitting region 3 arranged between a pair of device electrodes 5 and 6 on a substrate 1 is conducted in a manner as described below. In this operation, a monitoring device that has been subjected only to steps 1) and 2) of (A) and not to the electric forming operation is preferably used along with the device to be processed so that the end of the operation of chemically reducing the electroconductive film 4 of the device may be determined by observing changes in the resistance of the electroconductive film 4 of the monitoring device that has not been electrically formed and is concurrently subjected to the operation of chemical reduction.

Techniques that can be used for chemically reducing the electroconductive film 4 include the following.

20 (1) heating the film in vacuum

The heating temperature for this technique is preferably between 100°C and 400°C, although it depends on the degree of vacuum involved and the components of the electroconductive film.

25 (2) keeping the film in a reducing atmosphere

Gaseous substances that can be used for this technique include hydrogen, hydrogen sulfide, hydrogen

1 iodide, carbon monoxide, sulfur dioxide and other lower
gaseous oxides. The heating temperature for this
technique is preferably between room temperature (20°C)
and 400°C, although it depends on the gaseous substance
5 involved.

(3) keeping the film in a reducing solution

Reducing solutions that can be used for this
technique include solutions of hydrazine, diimides,
formic acid, aldehydes and L-ascorbic acid. The heating
10 temperature for this technique is preferably between
20°C and 100°C.

5) The device that has undergone the above steps is
then subjected to an activation step which will be
described below.

15 In this activation step, a pulse voltage having
a constant wave height is repeatedly applied to the
device in vacuum of a degree typically between 10^{-4}
and 10^{-5} torr as in the case of the forming operation so
that carbon or carbon compounds may be deposited on the
20 device out of the organic substances existing in the
vacuum in order to cause the device current I_f and the
emission current I_e of the device to change markedly
and obtain an electron-emitting device having a high
emission current I_e and a high electron emission
25 efficiency $((I_e/I_f) \times 100\{\%\})$.

The carbon or carbon compounds as referred to
above are found to be mostly graphite (both mono- and

1 poly-crystalline) and non-crystalline carbon (or a
mixture of amorphous carbon and poly-crystalline
graphite) if observed through a TEM or a Raman
spectroscopes and the thickness of the film deposited
5 is preferably less than 500 angstroms and more prefer-
ably less than 300 angstroms.

For the purpose of the present invention,
the activation step preferably precedes the chemical
reduction step.

10 More specifically, the electroconductive film
4 may show deformation on the surface due to agglom-
eration in the course of the chemical reduction
process to make the electron-emitting region 3 partly
short-circuited depending on the components of the
15 electroconductive film 4 and/or the conditions for
the operation of chemical reduction. Once such a
short-circuited state takes place, the device current
If can be increased to consequently reduce the ratio
of the electron emission current Ie to the device
20 current If.

The reduction in the ratio of the electron
emission current Ie to the device current If can be
prevented by forming a coating film on the electro-
conductive film 4 at a location near the electron-
25 emitting region 3 at the time of deposition of carbon
or carbon compounds in the activation step in order to
suppress any possible agglomeration and consequent

1 deformation of the electroconductive film 4 in the
succeeding chemical reduction step.

6) The prepared electron-emitting device is preferably
driving to operate in vacuum of a degree higher than
5 those of the electric forming step and the activation
steps. Preferably, the device is heated at 80°C to
150°C in vacuum of such a high degree. The degree of
vacuum higher than those of the electric forming step
and the activation step typically means a vacuum of
10 not higher than 10^{-6} torr and, preferably an ultra-high
vacuum state under which carbon and carbon compounds
would not be additionally deposited.

Thus, any additional deposition of carbon and/or
carbon compounds is suppressed to stabilize both the
15 device current I_f and the emission current I_e .

Now, some of the basic features of an
electron-emitting device according to the invention
and prepared in the above described manner will be
described below by referring to Fig. 6.

20 Fig. 6 shows a graph schematically illustrating
the relationship between the device voltage V_f and the
emission current I_e and between the device voltage V_f
and the device current I_f typically observed by the
measuring system of Fig. 4. Note that different units
25 are arbitrarily selected for I_e and I_f in Fig. 6 in
view of the fact that I_e has a magnitude by far smaller
than that of I_f .

1 As seen in Fig. 6, an electron-emitting device
according to the invention has three remarkable
features in terms of emission current I_e , which will
be described below.

5 Firstly, an electron-emitting device according
to the invention shows a sudden and sharp increase in
the emission current I_e when the voltage applied
thereto exceeds a certain level (which is referred to
as a threshold voltage hereinafter and indicated by
10 V_{th} in Fig. 6), whereas the emission current I_e is
practically undetectable when the applied voltage is
found lower than the threshold value V_{th} . Differently
stated, an electron-emitting device according to the
invention is a non-linear device having a clear
15 threshold voltage V_{th} to the emission current I_e .

Secondly, since the emission current I_e is
highly dependent on the device voltage V_f , the
former can be effectively controlled by way of the
latter.

20 Thirdly, the emitted electric charge captured
by the anode 34 is a function of the duration of time
of application of the device voltage V_f . In other
words, the amount of electric charge captured by the
anode 34 can be effectively controlled by way of the
25 time during which the device voltage V_f is applied.

Note that the device current I_f either
monotonically increases relative to the device voltage

1 Vf (as shown by a solid line in Fig. 6, a character-
istic referred to as MI characteristic hereinafter) or
changes to show a form specific to a voltage-controlled-
negative-resistance characteristic (as shown by a broken
5 line in Fig. 6, a characteristic referred to as VCNR
characteristic hereinafter). These characteristics of
the device current are dependent on a number of factors
including the manufacturing method, the conditions
where it is measured and the environment for operating
10 the device. The MI characteristic is preferably used
for the purpose of the present invention.

Now, a flat type surface conduction electron-
emitting device will be described.

Figs. 7A and 7B respectively show a schematic
15 plan view and a schematic sectional view of a surface
conduction electron-emitting device produced by a
manufacturing method according to the invention.
Referring to Figs. 7A and 7B, the device comprises a
substrate 1, a pair of device electrodes 5 and 6, a
20 thin film 4 including an electron-emitting region 3.

Materials that can be used for the substrate 1
include quartz glass, glass containing impurities such
as Na to a reduced concentration level, soda lime glass,
glass substrate realized by forming an SiO_2 layer on
25 soda lime glass by means of sputtering, ceramic
substances such as alumina.

While the oppositely arranged device electrodes

1 5 and 6 may be made of any highly conducting material,
preferred candidate materials include metals such as
Ni, Cr, Au, Mo, W, Pt, Ti, Al, Cu and Pd and their
alloys, printable conducting materials made of a
5 metal or a metal oxide selected from Pd, Ag, RuO_2 ,
Pd-Ag and glass, transparent electroconductive
materials such as In_2O_3 - SnO_2 and semiconductor
materials such as polysilicon.

The distance L separating the device electrodes,
10 the length W of the device electrodes, the contour of
the electroconductive film 4 and other factors for
designing a surface conduction electron-emitting device
according to the invention may be determined depending
on the application of the device. The distance L is
15 preferably between several hundreds angstroms and
several hundreds micrometers and, still preferably,
between several micrometers and tens of several
micrometers depending on the voltage to be applied to
the device electrodes and the field strength available
20 for electron emission.

The electroconductive thin film 4 is preferably
a fine particle film in order to provide excellent
electron-emitting characteristics. The thickness of
the electroconductive thin film 4 is determined as a
25 function of the stepped coverage of the thin film on
the device electrodes 5 and 6, the electric resistance
between the device electrodes 5 and 6 and the

1 parameters for the forming operation that will be
described later as well as other factors and prefer-
ably between several angstroms and several thousands
angstroms and more preferably between ten angstroms
5 and five hundreds angstroms.

The electroconductive film 4 is typically made
of fine particles of a material selected from metals
such as Pd, Ru, Ag, Ti, In, Cu, Cr, Fe, Zn, Sn, W and
Pb after processed in the above described chemical
10 reduction step, although it may contain oxides of
those metals such as PdO, SnO₂, In₂O₃, PbO, MoO and MoO₂.

The term "a fine particle film" as used herein
refers to a thin film constituted of a large number
of fine particles that may be loosely dispersed,
15 tightly arranged or mutually and randomly overlapping
(to form an island structure under certain conditions).
The diameter of fine particles to be used for the
purpose of the present invention is between several
angstroms and several thousands angstroms and preferably
20 between ten angstroms and two hundreds angstroms.

The electron-emitting region 3 is part of the
electroconductive thin film 4 and comprises
electrically highly resistive fissures, although its
profile is dependent on the thickness and the material
25 of the electroconductive thin film 4 and the electric
forming process described earlier. It may contain
electroconductive fine particles having a diameter

1 between several angstroms and hundreds of several
angstroms. The material of such fine particles may be
formed of all or part of the materials that are used
to prepare the electroconductive thin film 4. The
5 electroconductive thin film 4 preferably contains
carbon and carbon compounds in the electron-emitting
region 3 and its neighboring areas.

Now, a step type surface conduction electron-
emitting device, will be described.

10 Fig. 8 is a schematic sectional view of a step
type surface conduction electron-emitting device,
showing its basic configuration. The components same
as or similar to those of the device of Figs. 7A and 7B are
respectively denoted by the same reference symbols.

15 The device comprises a substrate 1, a pair of
device electrodes 5 and 6 and a electroconductive film
4 including an electron emitting region 3, which are
made of materials same as a flat type surface conduction
electron-emitting device as described above, as well as
20 a step-forming section 21 made of an insulating
material such as SiO_2 produced by vacuum deposition,
printing or sputtering and having a film thickness
corresponding to the distance L separating the device
electrodes of a flat type surface conduction electron-
25 emitting device as described above, or between several
hundreds angstroms and tens of several micrometers and
preferably between several hundreds angstroms and
several micrometers, although it is selected as a

1 function of the method of producing the step-forming
section used there, the voltage to be applied to the
device electrodes and the field strength available
for electron emission.

5 As the electroconductive film 4 is formed
after the device electrodes 5 and 6 and the step-
forming section 21, it may preferably be laid on the
device electrodes 5 and 6. The location and contour
of the electro-emitting region 3 are dependent on the
10 conditions under which it is prepared, electric
forming conditions and other related conditions and
not limited to the location and contour shown in Fig.
8.

Since an electron-emitting device produced by
15 a method according to the invention is provided with
the above described three remarkable features, its
electron-emitting performance can be easily and
accurately controlled as a function of input signals
even if it is used as one of a plurality of identical
20 electron-emitting devices comprised in an electron
source or an image-forming apparatus incorporating
such an electron source.

Then, an electron source and an image-forming
apparatus comprising electron-emitting devices produced
25 by a manufacturing method according to the invention
will be described in terms of their respective basic
configurations.

1 An electron source and an image-forming
apparatus can be realized by arranging a plurality of
electron-emitting devices on a substrate. Electron-
emitting devices may be arranged on a substrate in a
5 number of different modes. For instance, a number of
surface conduction electron-emitting devices as
described earlier may be arranged in rows along a
direction (hereinafter referred to row-direction),
each device being connected by wirings at opposite
10 ends thereof, and driven to operate by control
electrodes (hereinafter referred to as grids or
modulation means) arranged in a space above the
electron-emitting devices along a direction perpen-
dicular to the row direction (hereinafter referred
15 to as column-direction) or, alternatively as described
below, a total of m X-directional wirings and a total
of n Y-directional wirings are arranged with an
interlayer insulation layer disposed between the X-
directional wirings and the Y-directional wirings along
20 with a number of surface conduction electron-emitting
devices such that the pair of device electrodes of each
surface conduction electron-emitting device are
connected respectively to one of the X-directional
wirings and one of the Y-directional wirings. The
25 latter arrangement is referred to as a simple matrix
arrangement.

Now, the simple matrix arrangement will be

1 described in detail.

In view of the three basic features of a surface conduction electron-emitting device according to the invention, each of the surface conduction
5 electron-emitting devices in a configuration of simple matrix arrangement can be controlled for electron emission by controlling the wave height and the pulse width of the pulse voltage applied to the opposite electrodes of the device above the threshold voltage
10 level. On the other hand, the device does not emit any electron below the threshold voltage level. Therefore, in the case of a number of electron-emitting devices, desired surface conduction electron-emitting devices can be selected and controlled for
15 electron emission in response to the input signal by applying a pulse voltage to each of the selected devices.

Fig. 9 is a schematic plan view of the substrate of an electron source according to the invention
20 realized by using the above features. In Fig. 9, the electron source comprises a substrate 91 carrying a plurality of surface conduction electron-emitting devices arranged thereon (hereinafter referred to a electron source substrate), X-directional wirings 92,
25 Y-directional wirings 93, surface conduction electron-emitting devices 94 and connecting wires 95. The surface conduction electron-emitting devices may be

1 either of the flat type or of the step type. In Fig.
9, the electron source substrate 91 may be a glass
substrate and the number and configuration of the
surface conduction electron-emitting devices arranged
5 on the substrate may be appropriately determined
depending on the application of the electron source.

There are provided a total of m X-directional
wirings 92, which are denoted by DX1, DX2, ..., DX m
and made of an electroconductive metal formed by
10 vacuum deposition, printing or sputtering. These
wirings are so designed in terms of material, thickness
and width that a substantially equal voltage may be
applied to the surface conduction electron-emitting
devices. A total of n Y-directional wirings are
15 arranged and denoted by DY1, DY2, ..., DY n , which are
similar to the X-directional wirings 92 in terms of
material, thickness and width. An interlayer
insulation layer (not shown) is disposed between the
 m X-directional wirings 92 and the n Y-directional
20 wirings 93 to electrically isolate them from each
other, the m X-directional wirings and n Y-directional
wirings forming a matrix. Note that m and n are
integers.

The interlayer insulation layer (not shown) is
25 typically made of SiO_2 and formed on the entire surface
or part of the surface of the insulating substrate 91
to show a desired contour by means of vacuum

1 deposition, printing or sputtering. The thickness,
material and manufacturing method of the interlayer
insulation layer are so selected as to make it with-
stand any potential difference between an X-
5 directional wiring 92 and a Y-directional wiring 93
at the crossing thereof. Each of the X-directional
wirings 92 and the Y-directional wirings 93 is drawn
out to form an external terminal.

The oppositely arranged electrodes (not shown)
10 of each of the surface conduction electron-emitting
devices 94 are connected to the related one of the m
X-directional wirings 92 and the related one of the n
Y-directional wirings 93 by respective connecting wires
95 which are made of an electroconductive metal and
15 formed by vacuum deposition, printing or sputtering.

The electroconductive metal material of the
device electrodes and that of the connecting wires 95
extending from the m X-directional wirings 92 and the
n Y-directional wirings 93 may be same or contain
20 common elements are components, the latter being
appropriately selected depending on the former. If
the device electrodes and the connecting wires are made
of a same material, they may be collectively called
device electrodes without discriminating the connecting
25 wires. The surface conduction electron-emitting
devices may be arranged directly on the substrate 91
or on the interlayer insulation layer (not shown).

1 As will be described in greater detail
hereinafter, the X-directional wirings 92 are
electrically connected to a scan signal generating
means (not shown) for applying a scan signal to a
5 selected row of surface conduction electron-emitting
devices 94 and scanning the selected row according to
an input signal.

On the other hand, the Y-directional wirings
93 are electrically connected to a modulation signal
10 generating means (not shown) for applying a modulation
signal to a selected column of surface conduction
electron-emitting devices 94 and modulating the
selected column according to an input signal.

Note that the drive signal to be applied to
15 each surface conduction electron-emitting device is
expressed as the voltage difference of the scan
signal and the modulation signal applied to the
device.

With the arrangement of simple matrix wiring
20 as described above, an electron source according to
the invention can selectively and independently drive
individual electron-emitting devices.

Now, an image-forming apparatus according to
the invention and comprising an electron source having
25 a simple matrix arrangement as described above will
be described by referring to Figs. 10, 11A, 11B and
12. This apparatus may be a display apparatus.

1 Fig. 10 illustrates the basic configuration of
the display panel of the image-forming apparatus and
Figs. 11A and 11B show two alternative fluorescent
films that can be used for the purpose of the
5 invention, while Fig. 12 is a block diagram of the
drive circuit of the image-forming apparatus which is
adapted for the NTSC system.

Referring firstly to Fig. 10, the apparatus
comprises an electron source substrate 91 of the above
10 described type, a rear plate 101 rigidly holding the
electron source substrate 91, a face plate 106
produced by laying a fluorescent film 104 and a metal
back 105 on the inner surface of a glass substrate 103
and a support frame 102. An envelope 108 is formed
15 for the apparatus as frit glass is applied to said
rear plate 101, said support frame 102 and said face
plate 106, which are subsequently baked to 400 to 500°C
in the atmosphere or in nitrogen and bonded together to
a hermetically sealed condition.

20 In Fig. 10, reference numeral 94 denotes the
electron-emitting region of each electron-emitting
device as illustrated in Fig. 9 and reference numerals
92 and 93 respectively denotes the X-directional
wiring and the Y-directional wiring connected to the
25 respective device electrodes of each electron-emitting
device.

While the envelope 108 is formed of the face

1 plate 106, the support frame 102 and the rear plate 101
in the above description, the rear plate 101 may be
omitted if the substrate 91 is strong enough by itself
because the rear plate 101 is provided mainly for
5 reinforcement. If such is the case, an independent
rear plate 101 may not be required and the substrate
91 may be directly bonded to the support frame 102 so
that the envelope 108 is constituted of a face plate
106, a support frame 102 and a substrate 101. The
10 overall strength against the atmospheric pressure of
the envelope 108 may be increased by arranging a
number of support members called spacers (not shown)
between the face plate 106 and the rear plate 101.

Figs. 11A and 11B schematically illustrate two
15 possible arrangements of fluorescent bodies to form
a fluorescent film 104. While the fluorescent film
104 comprises only fluorescent bodies if the display
panel is used for showing black and white pictures, it
needs to comprise for displaying color pictures black
20 conductive members 111 and fluorescent bodies 112, of
which the former are referred to as black stripes or
members of a black matrix depending on the arrangement
of the fluorescent bodies. Black stripes or members
of a black matrix are arranged for a color display
25 panel so that the fluorescent bodies 112 of three
different primary colors are made less discriminable
and the adverse effect of reducing the contrast of

1 displayed images of external light is weakened by
blackening the surrounding areas. While carbon black
is normally used as a principal ingredient of the
black stripes, other conductive material having low
5 light transmissivity and reflectivity may alternatively be used.

A precipitation or printing technique may suitably be used for applying a fluorescent material on the glass substrate 103 regardless of black and
10 white or color display.

An ordinary metal back 105 is arranged on the inner surface of the fluorescent film 104. The metal back 105 is provided in order to enhance the luminance of the display panel by causing the rays of light
15 emitted from the fluorescent bodies and directed to the inside of the envelope to turn back toward the face plate 106, to use it as an electrode for applying an accelerating voltage to electron beams and to protect the fluorescent bodies against damages that
20 may be caused when negative ions generated inside the envelope collide with them. It is prepared by smoothing the inner surface of the fluorescent film 104 (in an operation normally called "filming") and forming an Al film thereon by vacuum deposition after
25 forming the fluorescent film 104.

A transparent electrode (not shown) may be formed on the face plate 106 facing the outer surface

1 of the fluorescent film 104 in order to raise the
conductivity of the fluorescent film 104.

Care should be taken to accurately align each
set of color fluorescent bodies and an electron-
5 emitting device, if a color display is involved,
before the above listed components of the enclosure
are bonded together.

The envelope 108 is then evacuated by way of
an exhaust pipe (not shown) to a degree of vacuum of
10 approximately 10^{-7} torr and hermetically sealed. A
getter operation may be carried out after sealing the
envelope 108 in order to maintain that degree of
vacuum in it. A getter operation is an operation of
heating a getter (not shown) arranged at a given
15 location in the envelope 108 immediately before or
after sealing the envelope 108 by resistance heating
or high frequency heating to produce a vapor deposition
film. A getter normally contains Ba as a principle
ingredient and the formed vapor deposition film can
20 typically maintain the inside of the enclosure to a
degree of 1×10^{-5} to 10^{-7} torr by its adsorption effect.

Fig. 12 shows a block diagram of the drive
circuit for driving the display panel of an image-
forming apparatus comprising an electron source having
25 a simple matrix arrangement as described above, said
apparatus being designed for image display operation
using NTSC television signals.

1 In Fig. 12, reference numeral 121 denotes the
display panel. The circuit further comprises a scan
circuit 122, a control circuit 123, a shift register
124, a line memory 125, a synchronizing signal
5 separation circuit 126, a modulation signal generator
127 and a pair of DC voltage sources V_x and V_a .

Each component of the apparatus operates in a
manner as described below. The display panel 121 is
connected to external circuits via terminals Dox1
10 through Doxm, Doyl through Doym and a high voltage
terminal Hv, of which terminals Dox1 through Doxm are
designed to receive scan signals for sequentially
driving on a one-by-one basis the rows (of a total of
N devices) of surface conduction electron-emitting
15 devices arranged in the form of a matrix having M rows
and N columns in the electron source. On the other
hand, terminals Doyl through Doyn are designed to
receive a modulation signal for controlling the output
electron beam of each of the surface-conduction type
20 electron-emitting devices of a row selected by a scan
signal. High voltage terminal Hv is fed by the DC
voltage source V_a with a DC voltage of a level
typically around 10kV, which is sufficiently high
to energize the fluorescent bodies of the selected
25 surface-conduction type electron-emitting devices.

The scan circuit 122 operates in a manner as
follows.

1 The scan circuit 122 comprises M switching
devices (which are schematically shown and denoted by
symbols S1 and Sm in Fig. 12), each of which takes
either the output voltage of the DC voltage source Vx
5 or 0V (the ground potential) and comes to be connected
with one of the terminals Dox1 through Doxm of the
display panel 121. Each of the switching devices S1
through Sm operates in accordance with control signal
Tscan fed from the control circuit 123 and can be
10 easily prepared by combining transistors such as FETs.

 The DC voltage source Vx of this mode of
carrying out the invention is designed to output a
constant voltage taking the characteristic properties
(including the threshold voltage for electron emission)
15 of the surface conduction electron-emitting devices
into consideration.

 The control circuit 123 coordinates the
operations of related components so that images may
be appropriately displayed in accordance with
20 externally fed picture signals. It generates control
signals Tscan, Tsft and Tmry for the related components
in response to synchronizing signal Tsync fed from the
synchronizing signal separation circuit 126. These
control signals will be described later in greater
25 detail hereinafter.

 The synchronizing signal separation circuit 126
separates the synchronizing signal component and the

1 luminance signal component from an externally fed NTSC
television signal and can be easily realized using a
popularly known frequency separation (filter) circuit.
Although a synchronizing signal extracted from a
5 television signal by the synchronizing signal
separation circuit 126 is constituted, as well known,
of a vertical synchronizing signal and a horizontal
synchronizing signal, it is simply designated as Tsync
signal here for convenience sake, disregarding its
10 component signals. On the other hand, a luminance
signal drawn from a television signal, which is fed to
the shift register 124, is designed as DATA signal.

The shift register 124 carries out for each
line a serial/parallel conversion on DATA signals
15 that are serially fed on a time series basis in
accordance with control signal Tsft fed from the
control circuit 123. In other words, a control signal
Tsft operates as a shift clock for the shift register
124. A set of data for a line that have undergone a
20 serial/parallel conversion (and correspond to a set
of drive data for N electron-emitting devices) are
sent out of the shift register 124 as n parallel
signals Id1 through Idn.

The line memory 125 is a memory for storing
25 a set of data for a line, which are signals Id1
through Idn, for a required period of time according
to control signal Tmry coming from the control circuit

1 123. The stored data are sent out as I'dl through
I'dn and fed to modulation signal generator 127.

The modulation signal generator 127 is in fact
a signal source that appropriately drives and
5 modulates the operation of each of the surface-
conduction type electron-emitting devices according to
each of the picture data I'dl through D'dn and output
signals of this device are fed to the surface-
conduction type electron-emitting devices in the
10 display panel 121 via terminals Doyl through Doyn.

As described above, an electron-emitting
devices according to the present invention is
characterized by the following features in terms of
emission current I_e . There exists a clear threshold
15 voltage V_{th} and the electron-emitting devices emit
substantially no electron when a voltage that falls
short of the threshold voltage V_{th} is applied thereto.

On the other hand, when the voltage applied
to the surface conduction electron-emitting devices
20 exceeds the threshold level, the rate of electron
emission of the surface conduction electron-emitting
devices varies as a function of the voltage applied
thereto. While the threshold voltage V_{th} for
electron emission and the rate of electron emission
25 relative to the applied voltage may vary depending on
the materials, the configuration and the manufacturing
method of electron-emitting devices, the following

1 statement always holds true.

When a pulse-shaped voltage is applied to an
electron-emitting device according to the invention,
it emits substantially no electron if the applied
5 voltage is found below the threshold voltage, for
electron emission but starts emitting electrons once
the applied voltage exceeds the threshold level. Thus,
firstly the rate of electron beam emission of the
device can be controlled by appropriately changing the
10 wave height, or amplitude V_m , of the pulse-shaped
voltage. Secondly, the total electric charge of the
electron beams being emitted by the device can be
controlled by appropriately changing the pulse width
Pw of the applied voltage.

15 Therefore, the electron-emitting device can be
modulated as a function of input signals either by
voltage modulation or by pulse width modulation.
The modulation signal generator 127 to be used for
voltage modulation may comprise a circuit that
20 generates a voltage pulse having a constant width and
a variable wave height that varies as a function of
input data.

On the other hand, the modulation signal
generator 127 to be used for pulse width modulation
25 comprises a circuit for generating a voltage pulse
having a constant wave height and a variable pulse
width that varies as a function of input data.

1 As a result of coordinated operation of the
above described components, television images are
displayed on the display panel 121 of the apparatus.
Although it is not particularly mentioned above that
5 the shift register 124 and the line memory 125 may be
either of digital or of analog signal type so long as
serial/parallel conversions and storage of video
signals are conducted at a given rate.

 If digital signal type devices are used, output
10 signal DATA of the synchronizing signal separation
circuit 126 needs to be digitized. However, such
conversion can be easily carried out by arranging an
A/D converter at the output of the synchronizing signal
separation circuit 126. In connection with this, it
15 should be noted that the circuit to be used for the
modulation signal generator 127 may have to be slightly
modified depending on if digital or analog signals are
produced by the line memory 125.

 More specifically, when digital signals are
20 used for voltage modulation, the modulation signal
generator 127 may suitably comprise a D/A conversion
circuit, to which an amplifying circuit may appropriately
be added if necessary. For pulse width modulation, the
modulation signal generator 127 may use a circuit
25 typically comprising in combination a high speed
oscillator, a counter for counting the number of
waves produced by the oscillator and a comparator for

1 comparing the output value of said counter and that
of said memory. If necessary, an amplifier may
additionally be used to amplify the voltage of the
modulation signal produced by the comparator and
5 modulated for pulse width to the level of the drive
voltage of the surface conduction electron-emitting
device.

When, on the other hand, analog signals are
used for voltage modulation, the modulation signal
10 generator 127 may suitably comprise an amplifying
circuit involving an operational amplifier and a level
shift circuit may appropriately be added thereto if
necessary. For pulse width modulation, the modulation
signal generator 127 may comprise a voltage control
15 type oscillation circuit (VCO), to which an amplifier
may be added to amplify the voltage of the modulation
signal to the level of the drive voltage of the surface
conduction electron-emitting device.

With an image-forming apparatus according to
20 the invention and having a configuration as described
above, the electron-emitting devices are selectively
caused to emit electrons by applying a device voltage
to them via the terminals Dox1 through Doxm and Doy1
through Doyn that are external to the envelope while
25 applying a high voltage to the metal back 105 or the
transparent electrode (not shown) via the high voltage
terminal Hv in order to accelerate the emitted electron

1 beams until they collide with an energize the
fluorescent film 104 so that the latter emits light
and display images.

While the configuration of an image-forming
5 apparatus according to the invention is schematically
described above, the materials and details of the
components are not limited to the above description and
may be modified appropriately depending on the appli-
cation of the apparatus. While the present invention
10 is described above in terms of television image display
using the NTSC television signal system, the TV signal
system to be used is not limited to a particular one
and any other system such as PAL or SECAM may feasibly
be used with it. An image-forming apparatus according
15 to the invention is particularly suited for TV signals
involving a larger number of scanning lines typically
of a high definition TV system such as the MUSE system
because it can be used for a large display panel
comprising a large number of scanning lines.

20 Now, an electron source having a ladder-like
arrangement and an image-forming apparatus comprising
such an electron source will be described for basic
configuration by referring to Figs. 13A, 13B and 14.

Referring to Figs. 13A and 13B showing two
25 alternative ladder-like arrangements of electron-
emitting devices for an electron source, the electron
source comprises an electron source substrate 144, a

1 number of electron-emitting devices 131 and paired
common wirings Dx1 through Dx10 collectively denoted
by 132 for wiring the electron-emitting devices. The
electron-emitting devices 131 are arranged in a
5 plurality of parallel rows running along the 'X-
direction on the substrate 144 (hereinafter referred
to device rows).

With such an arrangement, the device rows of
the electron source can be independently driven by
10 applying a drive voltage to the common wiring pairs
(Dx1-Dx2, Dx3-Dx4, Dx5-Dx6, Dx7-Dx8, Dx9-Dx10).
In other words, a voltage higher than the threshold
voltage is applied to one or more than one device rows
that have to emit electron beams whereas a voltage
15 lower than the threshold level is applied to the
remaining device rows that are not expected to emit
electron beams. Alternatively, a single common
wiring may be used for any two adjacent device rows
(and common wirings Dx2 and Dx3, Dx4 and Dx5, Dx6 and
20 Dx7 and Dx8 and Dx9 may be replaced by respective
single common wirings).

Fig. 14 is a schematic perspective view of the
display panel of an image-forming apparatus according
to the invention incorporating an electron source
25 having a ladder-like arrangement of electron-emitting
devices. In Fig. 14, the display panel comprises grid
electrodes 140, each provided with a number of through

1 bores 141 for allowing electrons to pass therethrough,
external terminals Dox1, Dox2, ..., Doxm collectively
denoted by 142, external terminals G1, G2, ..., Gn
collectively denoted by 143 and connected to the
5 respective grid electrodes and an electron source
substrate 144 as shown in Fig. 13B. Note that the
same components are respectively denoted by the same
reference symbols in Figs. 13A, 13B and 14.

The display panel of Fig. 14 remarkably
10 differs from that of the image-forming apparatus of
Fig. 10 having a simple matrix arrangement in that it
additionally comprises grid electrodes 140 arranged
between the electron source substrate 144 and the face
plate 106.

15 As described above, strip-shaped grid electrodes
140 are arranged between the substrate 144 and the face
plate 106 in Fig. 14 and rectangularly relative to the
devices rows arranged in a ladder-like manner in such
a way that they can modulate electron beams emitted
20 from the surface conduction electron-emitting devices
of the electron source. The grid electrodes are
provided with circular through bores 141 that are as
many as the electron-emitting devices to make one-to-
one correspondence. However, the profile and the
25 location of the grid electrodes are not limited to
those of Fig. 14 and may be modified appropriately so
long as they are arranged near or around the electron-

1 emitting devices. Likewise, the through bores 141 may
be replaced by meshes or the like.

The external terminals 142 and the external
terminals for the grids 143 are electrically connected
5 to a control circuit (not shown).

An image-forming apparatus having a configuration as described above can control the fluorescent film for electron beam irradiation by simultaneously applying modulation signals to the columns of grid
10 electrodes for a single line of an image in synchronism with driving the electron-emitting devices on a row by row basis so that the image can be displayed on a line by line basis.

Thus, a display apparatus according to the
15 invention and having a configuration as described above can have a wide variety of industrial and commercial applications because it can operate as a display apparatus for television broadcasting, as a terminal apparatus for video teleconferencing and as
20 an optical printer if it is combined with a photo-sensing drum.

[Examples]

Now, the present invention will be described in greater detail by way of examples.

25 (Example 1)

The method of manufacturing electron-emitting devices will be described below in terms of an

1 experiment conducted on specimens, referring to Figs.
7A and 7B and Figs. 3A to 3C.

Step a:

After thoroughly cleansing a soda lime glass
5 plate a silicon oxide film was formed thereon to a
thickness of 0.5 microns by sputtering to produce a
substrate 1, on which a pattern of photoresist (RD-
2000N-41: available from Hitachi Chemical Co., Ltd.)
was formed for a pair of device electrodes and a gap
10 separating the electrodes and then Ti and Ni were
sequentially deposited thereon respectively to thick-
nesses of 50Å and 1,000Å by vacuum deposition. The
photoresist pattern was dissolved in an organic solvent
and the Ni/Ti deposit film was treated by using a
15 lift-off technique to produce a pair of device
electrodes 5 and 6 having a width W of 300 microns and
separated from each other by a distance L of 20 microns
(Fig. 3A).

Step b:

20 A mask having opening for the gap L separating
the device electrodes and its vicinity was used to form
a Cr film to a film thickness of 1,000Å by vacuum
deposition, which was then subjected to a patterning
operation. Thereafter, organic Pd (ccp4230: available
25 from Okuno Pharmaceutical Co., Ltd.) was applied to the
Cr film by means of a spinner, while rotating the film,
and baked at 300°C for 10 minutes to produce an

1 electroconductive film for forming an electron-emitting
region, which was made of fine particles containing
PdOx as a principal ingredient and had a film thickness
of 100 angstroms and an electric resistance per unit
5 area of $5 \times 10^4 \Omega/\square$.

Note that the term "a fine particle film" as
used herein refers to a thin film constituted of a
large number of fine particles that may be loosely
dispersed, tightly arranged or mutually and randomly
10 overlapping (to form an island structure under certain
conditions). The diameter of fine particles to be
used for the purpose of the present invention is that
of recognizable fine particles arranged in any of the
above described states.

15 Step c:

The Cr film and the baked electroconductive
film for forming an electron-emitting region were
etched by using an acidic etchant to produce an
electroconductive film 4 having a desired pattern
20 (Fig. 3B).

Now, a device having a pair of device
electrodes and an electroconductive film disposed
between the electrodes on the substrate was prepared.

Step d:

25 Then, the substrate of the device was set in
position in a gauging system as illustrated in Fig. 4
and the inside of the vacuum chamber of the system was

1 evacuated by means of an exhaust pump to a degree of
vacuum of 1×10^{-6} torr. Subsequently, a voltage V_f was
applied for 60 seconds from the power source 31 to the
device electrodes 5, 6 to electrically energize the
5 device (electric forming process) and produce a
locally deformed (fissured) section (electron emitting
region) 3 in the electroconductive film (Fig. 3C).

Fig. 5B shows the voltage waveform used for
the electric forming process.

10 In Fig. 5B, T_1 and T_2 respectively denote the
pulse width and the pulse interval of the applied
pulse voltage, which were respectively 1 millisecond
and 10 milliseconds for this example. The wave height
(the peak voltage for the forming operation) of the
15 applied pulse voltage was increased stepwise with steps
of 0.1V.

It was found that fine particles containing
palladium oxide as a principal ingredient were
dispersed in the electron emitting region 3 of the
20 device produced by following the above steps, the
average diameter of the particles being 30 angstroms.
Step e:

Subsequently, the electroconductive film 4 of
the device that had undergone an electric forming
25 operation was subjected to a chemical reduction process.

In this process, the device and a monitoring
device that had not been processed for electric forming

1 (but had undergone the steps of through c above) were
arranged in an apparatus having a configuration as
shown in Fig. 4 and then heated to 130°C to 200°C for
approximately 10 hours, while keeping the inside of the
5 apparatus to a degree of vacuum of 1×10^{-6} torr.

After the chemical reduction process, it was
found that the electroconductive film containing PdOx
as a principal ingredient of the monitoring device
without an electric forming process had been chemically
10 reduced to become a film of fine particles of Pd metal
having an electric resistance per unit area of 5×10^2
 Ω/\square or a value smaller than the resistance before the
chemical reduction by two digits.

In an attempt to see the properties of the
15 electron-emitting device prepared throughout the
preceding steps, it was observed for electron-emitting
performance, using a measuring system as illustrated
in Fig. 4. In the above observation, the distance H
between the anode 34 and the electron-emitting device
20 was 4mm and the potential of the anode 34 was 1kV,
while the degree of vacuum in the vacuum chamber of
the system was held to 1×10^{-6} torr throughout the
gauging operation.

A device voltage was applied between the
25 device electrodes 5, 6 of the device to see the device
current I_f and the emission current I_e under that
condition. Fig. 6 shows the current-voltage

1 relationships obtained as a result of the observation.

An emission current I_e began to flow through the device immediately when the device voltage (V_f) became as high as 8V and a device current I_f of 3.0
5 mA and an emission current of 1.5 microA were observed when the device voltage rose to 14V to provide an electron emission efficiency $\eta = I_e / I_f \times 100(\%)$ of 0.05%.

When the device was observed before the chemical reduction process, the film of PdO fine
10 particles (electroconductive film) of the device showed an electric resistance of 3.5k Ω and the fissured area had an electric resistance of 4.7k Ω . After the chemical reduction process, it was found that the electric resistance of the film of PdO fine
15 particles of the electron-emitting device was as low as 35 Ω , which was negligible when compared with that of the fissured area.

In other words, for an electron-emitting device after a chemical reduction process according to the
20 invention to obtain the same electron emission rate as a device before the process having required a device voltage of 24.6V, the device after the process required a power consumption rate of only 42 milliW whereas it was 73.8 milliW for the device before the
25 process, i.e. the former being 57% of the latter, thus proving a significant saving of power.
(Example 2)

1 This example relates to an electron source
 comprising a plurality of electron-emitting devices
 produced by the method of Example 1 and an image-
 forming apparatus incorporating such an electron
5 source.

 Fig. 15 shows a schematic partial plan view of
 the electron source and Fig. 16 shows a schematic
 partial sectional view taken along line A-A' of Fig.
 15, while Figs. 17A to 17F and 18G to 18I illustrate
10 schematic partial sectional views of the electron
 source shown in different manufacturing steps. Note
 that same or similar components are respectively
 designated by same reference symbols throughout Figs.
 15 through 18I.

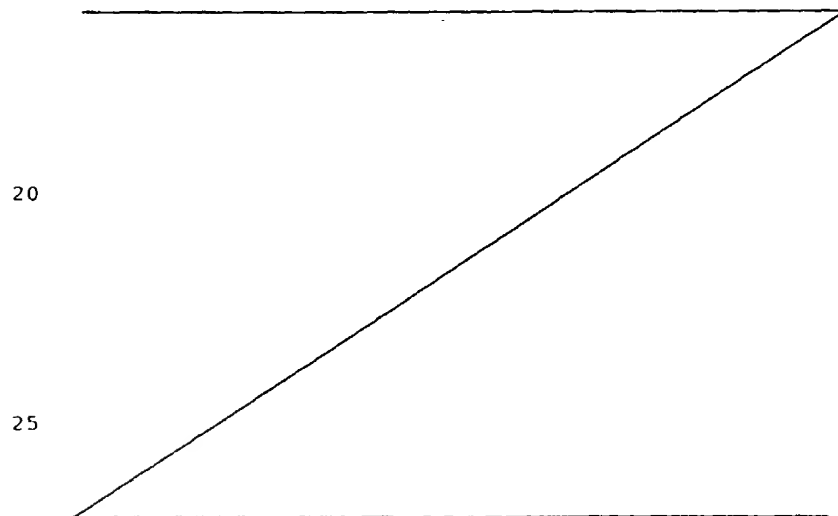
15 91 denotes a substrate and 92 and 93
 respectively denote X- and Y-directional wirings
 (which may be called lower and upper wirings
 respectively) that correspond to Dx_m and Dy_n in Fig.
 9. Otherwise, the electron source comprises electron-
20 emitting devices, each having an electroconductive
 film 4 and a pair of device electrodes 5 and 6, an
 interlayer insulation layer 161 and a number of contact
 holes, each of which is used to connect a device
 electrode 5 with a related lower wiring 92.

25 Now, the steps of manufacturing an electron
 source and an image-forming apparatus incorporating
 such as electron source used in this example will be

1 described in detail.

Step a:

After thoroughly cleansing a soda lime glass
plate a silicon oxide film was formed thereon, to a
5 thickness of 0.5 microns by sputtering to produce a
substrate 91, on which Cr and Au were sequentially
laid to thicknesses of 50 angstroms and 6,000
angstroms respectively and then a photoresist
(AZ1370: available from Hoechst Corporation) was formed
10 thereon by means of a spinner, while rotating the film,
and baked. Thereafter, a photo-mask image was exposed
to light and developed to produce a resist pattern for
the lower wirings 92 and then the deposited Au/Cr film
was wet-etched to produce lower wirings 92 having a
15 desired profile (Fig. 17A).



1 Step b:

A silicon oxide film was formed as an interlayer insulation layer 161 to a thickness of 1.0 micron by RF sputtering (Fig. 17B).

5 Step c:

A photoresist pattern was prepared for producing contact holes 162 in the silicon oxide film deposited in Step b, which contact holes 162 were then actually formed by etching the interlayer insulation layer 161, using the photoresist pattern for a mask (Fig. 17C).

RIE (Reactive Ion Etching) using CF_4 and H_2 gas was employed for the etching operation.

Step d:

Thereafter, a pattern of photoresist (RD-2000N-41: available from Hitachi Chemical Co., Ltd.) was formed for pairs of device electrodes 5 and 6 and gaps L1 separating the respective pairs of electrodes and then Ti and Ni were sequentially deposited thereon respectively to thicknesses of 50 Å and 1,000 Å by vacuum deposition. The photoresist pattern was dissolved by an organic solvent and the Ni/Ti deposit film was treated by using a lift-off technique to produce pairs of device electrodes 5 and 6, each pair having a width of 300 microns and separated from each other by a distance L1 of 20 microns (Fig. 17D).

Step e:

After forming a photoresist pattern on the device

1 electrodes 5, 6 for upper wirings 93, Ti and Au were
sequentially deposited by vacuum deposition to
respective thicknesses of 50 angstroms and 5,000
angstroms and then unnecessary areas were removed by
5 means of a lift-off technique to produce upper wirings
93 having a desired profile (Fig. 17E).

Step f:

A mask was prepared for the electroconductive
films 2 of the devices.

10 The mask had an opening for the gap L1
separating the device electrodes and its vicinity of
each device. The mask was used to form a Cr film 171
to a film thickness of 1,000 Å by vacuum deposition,
which was then subjected to a patterning operation.
15 Thereafter, organic Pd (ccp4230: available from Okuno
Pharmaceutical Co., Ltd.) was applied to the Cr film
by means of a spinner, while rotating the film, and
baked at 300°C for 10 minutes (Fig. 17F).

The formed electroconductive films 2 were made
20 of fine particles containing PdOx as a principal
ingredient and had a film thickness of 100 angstroms
and an electric resistance per unit area of $5 \times 10^4 \Omega/\square$.

Note that the term "a fine particle film" as
used herein refers to a thin film constituted of a
25 large number of fine particles that may be loosely
dispersed, tightly arranged or mutually and randomly
overlapping (to form an island structure under certain

1 conditions). The diameter of fine particles to be used
for the purpose of the present invention is that of
recognizable fine particles arranged in any of the
above described states.

5 Step g:

The Cr film 171 and the baked electroconductive
film 2 were etched by using an acidic etchant to produce
a desired pattern (Fig. 18G).

Step h:

10 Then, a pattern for applying photoresist to the
entire surface area except the contact holes 162 was
prepared and Ti and Au were sequentially deposited by
vacuum deposition to respective thicknesses of 50
angstroms and 5,000 angstroms. Any unnecessary areas
15 were removed by means of a lift-off technique to
consequently bury the contact holes 162 (Fig. 18H).

Now, lower wirings 92, an interlayer insulation
layer 161, upper wirings 93, and devices comprising
pairs of device electrodes 5 and 6 and electroconductive
20 films 2 were produced on the substrate 91.

Then, an electron source comprising the above
electron source substrate and an image-forming
apparatus incorporating such an electron source were
prepared. This will be described below by referring
25 to Figs. 10, 11A and 11B.

The substrate 91 carrying thereon a large number
of devices prepared according to the above described

1 process was rigidly fitted to a rear plate 101 and
thereafter a face plate 106 (prepared by forming a
fluorescent film 104 and a metal back 105 on a glass
substrate 103) was arranged 5 mm above the substrate
5 91 by interposing a support frame 102 therebetween.
Frit glass was applied to junction areas of the face
plate 106, the support frame 102 and the rear plate
101, which were then baked at 400°C for 15 minutes in
the atmosphere and bonded together to a hermetically
10 sealed condition (Fig. 10). The substrate 91 was also
firmly bonded to the rear plate 101 by means of frit
glass.

In Fig. 10, reference numerals 92 and 93
respectively denote X- and Y-directional wirings.

15 While the fluorescent film 104 may be solely
made of fluorescent bodies if the image-forming
apparatus is for black and white pictures, firstly
black stripes were arranged and then the gaps separating
the black stripes were filled with respective fluorescent
20 bodies for primary colors to produce a fluorescent film
104 for this example (Fig. 11A). The black stripes
were made of a popular material containing graphite as
a principal ingredient. The fluorescent bodies were
applied to the glass substrate 103 by using a slurry
25 method.

A metal back 105 is normally arranged on the
inner surface of the fluorescent film 104. In this

1 example, a metal back was prepared by producing an Al
film by vacuum deposition on the inner surface of the
fluorescent film 104 that had been smoothed in a so-
called filming process. The face plate 106 may be
5 additionally provided with transparent electrodes (not
shown) arranged close to the outer surface of the
fluorescent film 104 in order to improve the
conductivity of the fluorescent film 104, no such
electrodes were used in this example because the metal
10 back proved to be sufficiently conductive.

The fluorescent bodies were carefully aligned
with the respective devices before the above described
bonding operation.

The prepared glass container was then evacuated
15 by means of an exhaust pipe (not shown) and an exhaust
pump to achieve a sufficient degree of vacuum inside the
container. Thereafter, the electroconductive film 2 of
each of the devices arranged on the substrate 91 was
subjected to an electric forming operation, where a
20 voltage was applied to the device electrodes 5, 6 of the
devices by way of the external terminals Dox1 through
Doxm and Doyl through Doyn to produce an electron-
emitting region 3 in each electroconductive film 2.

The voltage used in the forming operation had
25 a waveform same as the one shown in Fig. 5B. Referring
to Fig. 5B, T1 and T2 were respectively 1 milliseconds
and 10 milliseconds and the electric forming operation

1 was carried out in vacuum of a degree of approximately
1 x 10⁻⁶ torr. The wave height (the peak voltage for
the forming operation) of the applied pulse voltage was
increased stepwise with steps of 0.1 V.

5 A monitoring device was also prepared without
subjecting them to an electric forming operation so that
it may be used to monitor the electric resistance of
each device during a subsequent chemical reduction
process, which will be described hereinafter.

10 Dispersed fine particles containing palladium
oxide as a principal ingredient were observed in the
electron-emitting regions 3 of the electron-emitting
devices that had been produced in the above process.
The fine particles had an average particle diameter
15 of 30 angstroms.

Step i:

Subsequently, the electroconductive film 4
including an electron-emitting region each of the
electron-emitting device was subjected to a chemical
20 reduction process (Fig. 18I).

In this process, the enclosure comprising a face
plate 106, a support frame 102 and a rear plate 101 was
evacuated by means of an exhaust pump to a degree of
vacuum of 1 x 10⁻⁶ torr and then the devices were
25 heated to 130°C to 200°C for approximately 10 hours in
the vacuum. After the chemical reduction process, it
was found that the electroconductive film 2 (film of

1 PdO fine particles) of the control device without an
electric forming process had been chemically reduced
to become a film of fine particles of Pd metal having
an electric resistance per unit area of $5 \times 10^2 \Omega/\square$
5 or a value smaller than the resistance before the
chemical reduction by two digits.

Thus, the operation of preparing an electron
source was completed as the devices arranged on the
substrate 91 had been subjected to an electric forming
10 operation to produce electron-emitting regions 3 and a
chemical reduction process.

Thereafter, the enclosure was evacuated to a
degree of vacuum of approximately of 10^{-6} torr and then
hermetically sealed by melting and closing the exhaust
15 pipe (not shown) by means of a gas burner.

The apparatus was subjected to a getter process
using a high frequency heating technique in order to
maintain the degree of vacuum in the apparatus after
the sealing operation, where a getter disposed at a
20 predetermined position (not shown) in the enclosure was
heated by high frequency heating immediately before the
sealing operation to form a film as a result of vapor
deposition. The getter is a material containing Ba as
a principal component.

25 The electron source having a simple matrix
arrangement as described above was then used to produce
an image-forming apparatus adapted for the NTSC television

1 system. The image-forming apparatus was complete with
a drive circuit as illustrated in Fig. 12 and described
earlier. Pulse modulation was used for the image-
forming apparatus.

5 The electron-emitting devices of the above
image-forming apparatus were then caused to emit
electrons by applying a drive voltage thereto through
the external terminals Dox1 through Doxm and Doyl through
Doyn and the emitted electrons were accelerated by
10 applying a high voltage of 10 kV to the metal back 105
via the high voltage terminal Hv so that they collides
with the fluorescent film 104 until the latter was
energized to emit light and produce images. As the
image-forming apparatus of this example had undergone a
15 chemical reduction process for the electroconductive
films of the electron-emitting devices in the process
of manufacturing them, it has a feature of low energy
consumption rate for operation.

(Example 3)

20 A chemical reduction process was carried out in
a reducing atmosphere for this example.

An electron-emitting device having a
configuration as illustrated in Figs. 7A, 7B was
prepared by following Steps a through e, of which
25 Steps a through d are same as those of Example 1 above.
So, only Step e will be described here.

1 Step e:

As in the case of Example 1, an electron-emitting device comprising a pair of electrodes 5 and 6 and an electroconductive film 4 including an electron-emitting region 3 arranged on a substrate 1 (Fig. 3C) and a monitoring device that had not been subjected to an electric forming operation (or that had undergone Steps a through c) were placed in a vacuum apparatus as shown in Fig. 4, into which nitrogen gas containing hydrogen by 2% was introduced from a reducing gas cylinder as shown in Fig. 19 until it showed a partial pressure of 1 millitorr at room temperature in the apparatus, when the devices were heated to temperature between 130°C and 200°C and kept to that temperature for approximately an hour.

After the chemical reduction process for an hour, it was found that the electroconductive film containing PdOx as a principal ingredient of the monitoring device without an electric forming process had been chemically reduced to become a film of fine particles of Pd metal having an electric resistance per unit area of $5 \times 10^2 \Omega/\square$ or a value smaller than the resistance before the chemical reduction by two digits.

In an attempt to see the properties of the electron-emitting device prepared through the preceding steps, it was observed for electron-emitting performance, using a gauging system as illustrated in Fig. 4. In

1 the above observation, the distance H between the anode
34 and the electron-emitting device was 4 mm and the
potential of the anode 34 was 1 kV, while the degree
of vacuum in the vacuum chamber of the system was
5 held to 1×10^{-6} torr throughout the gauging operation.

A device voltage was applied between the
device electrodes 5, 6 of the device to see the device
current I_f and the emission current I_e under that
condition. Fig. 6 shows the current-voltage
10 relationships obtained as a result of the observation.

An emission current I_e began to flow through
the device immediately when the device voltage (V_f)
became as high as 14 V and a device current I_e of 2.2
milliA and an emission current I_e of 1.1 microA were
15 observed when the device voltage rose to 14 V to
provide an electron emission efficiency $\theta = I_e/I_f \times 100(\%)$
of 0.05%.

When the device was observed before the chemical
reduction process, the film of PdO fine particles
20 (electroconductive film) of the device showed an
electric resistance of 3.5 k Ω and the fissured area
had an electric resistance of 6.4 k Ω . After the
chemical reduction process, it was found that the
electric resistance of the film of PdO fine particles
25 of the electron-emitting device that had undergone a
chemical reduction process (the device of this example)
was as low as 35 Ω , which was negligible when compared

1 with that of the fissured area.

In other words, for an electron-emitting device after a chemical reduction process according to the invention to obtain the same electron emission rate as a
5 device before the process having required a device voltage of 22 V, the device after the process required a power consumption rate of only 31 milliW, whereas it was only 48 milliW for the device before the process, i.e., the former being two thirds of the latter, thus proving a
10 significant saving of power.

Note that the duration of chemical reduction process was as short as an hour and this fact can greatly contribute to raising the rate of manufacturing electron-emitting devices of the type under consideration.
15 Additionally, since the chemical reduction process is conducted in an electric furnace under the atmospheric pressure, the entire facility required for manufacturing electron-emitting devices can be remarkably simplified.
(Example 4)

20 A total of twenty-five electron-emitting devices each having a configuration as shown in Figs. 7A and 7B were prepared.

The process of preparing the electron-emitting devices will be described below in terms of a single
25 device by referring to Figs. 3A to 3C and Figs. 7A and 7B.

1 Step a:

A silicon oxide film was formed on a thoroughly
cleansed soda lime glass plate to a thickness of 0.5
microns by sputtering to produce a substrate 1, on
5 which a pattern of photoresist (RD-2000N-41: available
from Hitachi Chemical Co., Ltd.) was formed for a pair
of device electrodes and a gap separating the electrodes
and then Ti and Ni were sequentially deposited thereon
respectively to thicknesses of 5 nm and 100 nm by vacuum
10 deposition.

The photoresist pattern was dissolved in an
organic solvent and the Ni/Ti deposit film was treated
by using a lift-off technique to produce a pair of
device electrodes 5 and 6 having a width W of 300
15 microns and separated from each other by a distance L
of 20 microns (Fig. 3A).

Step b:

A Cr film was deposited by vacuum deposition on
the entire surface of the substrate prepared in Step a
20 and including the device electrodes 5 and 6 to a film
thickness of 50 nm and then subjected to a patterning
operation, using a mask (not shown) having opening with
a length not smaller than L and a width W' for the gap
separating the device electrodes and its vicinity. The
25 film was then developed and etched for the opening to
expose the gap L separating the electrodes and part of
the device electrodes 5, 6, to produce a Cr mask having

1 a width W' of 100 μ m. Thereafter, organic Pd (ccp4230:
available from Okuno Pharmaceutical Co., Ltd.) was
applied to the Cr film by means of a spinner, while
rotating the film, and baked at 300°C for 10 minutes.
5 Thereafter, the Cr film was etched by an acidic etchant
and treated by using a lift-off technique to produce an
electroconductive film 4 (Fig. 3B).

The produced electroconductive film 4 was made
of fine particles containing PdO as a principal
10 ingredient and had a film thickness of 100 angstroms
and an electric resistance per unit area of $2 \times 10^4 \Omega/\square$.

Note that the term "a fine particle film" as
used herein refers to a thin film constituted of a
large number of fine particles that may be loosely
15 dispersed, tightly arranged or mutually and randomly
overlapping (to form an island structure under certain
conditions). The diameter of fine particles to be used
for the purpose of the present invention is that of
recognizable fine particles arranged in any of the above
20 described states.

Now, a pair of device electrodes 5, 6 and an
electronconductive film 4 were formed on the substrate
1 for all the devices through the above steps.
Step c:

25 Then, the devices were set in position in a
measuring system as illustrated in Fig. 4 and the
inside of the vacuum chamber of the system was evacuated

1 by means of an exhaust pump to a degree of vacuum of
2 2×10^{-5} torr. Subsequently, a voltage V_f was applied
3 from the power source 31 to the device electrodes 5, 6
4 of twenty four devices out of the twenty five devices to
5 electrically energize the devices (electric forming
process).

Fig. 5B shows the voltage waveform used for the
electric forming process.

In Fig. 5B, T_1 and T_2 respectively denote the
10 pulse width and the pulse interval of the applied pulse
voltage, which were respectively 1 millisecond and 10
milliseconds for this example. The wave height (the
peak voltage for the forming operation) of the applied
pulse voltage was increased stepwise with steps of 0.1 V.
15 During the electric forming operation, an additional
pulse voltage of 0.1 V was inserted in each interval of
 T_2 for measuring the resistance and the application of
pulse voltage was terminated to complete the electric
forming process when the resistance measured by using a
20 pulsed voltage exceeded about 1 M Ω .

In the period from the beginning to the end of
an electric forming process, the device current I_f gets
to a maximum level of I_{max} , the voltage (or the wave
height of the pulse voltage) corresponding to I_{max}
25 being denoted by forming voltage V_{form} .

The forming voltage V_{form} for the above devices
was approximately 7.0 V.

1 Step d:

Subsequently, a protective film forming operation was conducted on twelve out of the twenty four devices that had been subjected to the electric forming process. In this operation, a pulse voltage as shown in Fig. 5A and having a wave height value of 14 V was applied to the device electrodes 5, 6 of the devices in order to cause them emit electrons. The emitted electrons operated to decompose carbon compounds into carbon atoms, which were deposited on and near the electron-emitting regions 3 of the devices to produce a protective film.

The twelve devices subjected to the protective film forming operation are called devices A, whereas the remaining twelve devices not subjected to the protective film forming operation after the electric forming process are called devices B.

For the protective film forming operation, a pulse voltage was applied to the device electrodes 5, 6 of each device while observing the emission current I_e in the apparatus of Fig. 4, the inside of which apparatus was maintained to a degree of vacuum of 1.5×10^{-5} torr.

The emission current I_e became saturated in approximately 30 minutes, when the protective film forming operation was terminated.

1 Step e:

All the devices including the one that had not undergone an electric forming process were then subjected to a chemical reduction process.

5 In this operation, nitrogen gas containing hydrogen by 2% was introduced through a reducing gas inlet pipe (not shown) under the control of a mass flow controller (not shown) until it showed a partial pressure of 1 millitorr in the vacuum apparatus.

10 As the twenty five devices were exposed to this atmosphere for an hour, the electroconductive films 4 of the devices containing PdO as a principal ingredient were chemically reduced to become so many films of fine Pd particles that showed an electric resistance per unit
15 area of $5 \times 10^2 \Omega/\square$ or a value smaller than the resistance before the chemical reduction by two digits.

The change in the electric resistance of the films was confirmed by measuring the electric resistance between the device electrodes (hereinafter referred to as
20 device resistance) of the single electron-emitting device that had not been subjected to an electric forming operation before and after the chemical reduction process. More specifically, the device resistance of the device was 4 k Ω before the chemical reduction and
25 approximately 100 Ω after the chemical reduction.

In numerical terms, when an electron-emitting device prepared in a manner as described above is driven

1 under the above described condition, a device current
of approximately 1 mA flows through the device.

If the electroconductive film 4 of the device
is not chemically reduced, the device voltage shows a
5 drop of approximately 4 V at the electroconductive film
4 due to the relatively high electric resistance of the
lateral portions of the film arranged at the opposite
ends of the electron emitting region 3 to ineffectively
consume power at a rate of 4 mW.

10 As seen from the graph of current-voltage
relationship of a surface conduction electron-emitting
device illustrated in Fig. 6, the emission current
sharply or exponentially rises relative to the device
voltage when the latter gets to V_{th} . Therefore, an
15 electroconductive film 4 that has not been treated for
chemical reduction not only consumes power ineffectively
but also lowers the voltage applied to the electron
emitting region 3 and hence the rate of electron
emission as the voltage drops at the lateral portions
20 of the film.

So, in order for the emission current of an
electron-emitting device that has not been treated for
chemical reduction to become equal to that of an
electron-emitting device that has undergone a chemical
25 reduction process, the drive voltage of the former
device has to be made approximately 4 V higher than that
of the latter device.

1 In other words, a chemical reduction process is
highly effective for efficiently driving a surface
conduction electron-emitting device with a low voltage
and a low energy consumption rate.

5 In order to further look into the profile and
the performance of the surface conduction electron-
emitting devices prepared through the above steps, one
of the devices A and one of the devices B were picked up
and observed through an electron microscope and the
10 remaining devices were tested on a one by one basis in
the apparatus of Fig. 4. The electron-emitting device
to be tested was separated from the anode 34 by 4 mm
and a voltage of 1 kV was applied to the anode 34 while
maintaining the inside of the vacuum apparatus to a
15 degree of vacuum of 1×10^{-6} torr during the test.

A device voltage of 14 V was applied to each of
the tested devices A and B to see the device current I_f
and the emission current I_e .

When the twelve devices A is compared with the
20 twelve devices B, the average device current I_f of the
devices A was 1.0 mA and that of the devices B was
1.2 mA for the device voltage of 14 V whereas the
emission current I_e of the former was 0.5 microA and
that of the latter was 0.45 microA to provide an
25 electron emission efficiency $\theta = I_e/I_f \times 100(\%)$ of 0.05%
for the devices A and 0.04% for the devices B. The
standard deviation of the dispersed emission current

1 values relative to the average was approximately 6% for
the devices A and approximately 10% for the devices B.

From the above observations, it was proved that
the devices A had an ineffective current (part of the
5 device current that does not contribute to electron
emission) lower than that of the devices B and the
former were also superior to that latter in terms of
electron emission efficiency and uniformity.

As a result of electron microscope observation,
10 it was found that the sampled device A had a protective
film 11 at the interface of the electroconductive film 4
and the substrate 1 near the electron emitting region 3
on both the positive and negative sides as illustrated
in Fig. 20, although the protective film was
15 particularly remarkable on the positive electrode side.
While a similar film was observed on the sample device
B, it was markedly poor and not found in certain
necessary areas.

When observed through an FE-SEM having a large
20 magnification, it was found that the electroconductive
film 4 of fine particles of each of the devices B that
had been treated for chemical reduction without a
protective film had been partly deformed and displaced
in the vicinity of the electron emitting region 3. As
25 the electron emitting region 3 had been partly covered
back by the electroconductive film 4, the device
electrodes 5 and 6 were slightly short-circuited

1 through narrow routes of electric current. This might
prove that the electron emitting region 3 had been
partly destroyed as a result of chemical reduction.
Contrary to this, such phenomena were not observed on
5 the devices A that had been subjected to chemical
reduction with a protective film.

It seemed that the protective film 11 had also
been formed in periphery areas of and gaps separating
metal fine particles of the electroconductive film 4.
10 By observing the protective film through a TEM and a
Raman spectroscopy, it was found that the protective
film 11 was composed of carbon mainly in the form of
graphite and amorphous carbon or carbon compounds.

From the above observations, it can safely be
15 concluded that the electron emitting region 3 and the
remaining areas of the electroconductive film of fine
particles of each of the device B were partly destroyed
and displaced during the chemical reduction process as
the surface energy was activated on the electroconductive
20 film near and around the electron emitting region 3,
leading to differentiated performances among the
devices B. On the other hand, the protective film 11
of carbon or carbon compounds formed near and around the
electron emitting region 3 of each of the devices A
25 effectively prevented the electron emitting region 3
from being destroyed during the chemical reduction
process so that the reduction process proceeded stably

1 to produce uniform devices A.
(Example 5)

This example relates to an image-forming
apparatus comprising a plurality of electron-emitting
5 devices of the type A produced by the method of Example
2, where the electroconductive films 4 are made of SnO_2
and the electron-emitting devices are arranged to form
a simple matrix.

Fig. 15 shows a schematic partial plan view of
10 the electron source and Fig. 16 shows a schematic
partial sectional view taken along line A-A' of Fig.
15, while Figs. 17A - 17F and 18G - 18I illustrate
schematic partial sectional views of the electron
source shown in different manufacturing steps. Note
15 that same or similar components are respectively
designated by same reference symbols throughout
Figs. 15 through 18I.

91 denotes a substrate and 92 and 93 respectively
denote X- and Y-directional wirings (which may be called
20 lower and upper wirings respectively) that correspond to
Dxm and Dyn in Fig. 9. Otherwise, the electron source
comprises electron-emitting devices, each having an
electroconductive film 4 and a pair of device electrodes
5 and 6, an interlayer insulation layer 161 and a number
25 of contact holes, each of which is used to connect a
device electrode 5 with a related lower wiring 92.

Now, the steps of manufacturing an electron

1 source and an image-forming apparatus incorporating
such as electron source used in this example will be
described in detail.

Step a:

5 After thoroughly cleansing a soda lime glass
plate a silicon oxide film was formed thereon to a
thickness of 0.5 micrometers by sputtering to produce
a substrate 91, on which Cr and Au were sequentially
laid to thicknesses of 5.0 nm and 600 nm respectively
10 and then a photoresist (AZ1370: available from Hoechst
Corporation) was formed thereon by means of a spinner,
while rotating the film, and baked. Thereafter, a
photo-mask image was exposed to light and developed to
produce a resist pattern for the lower wirings 92 and
15 then the deposited Au/Cr film was wet-etched to produce
lower wiring 82 having a desired profile (Fig. 17A).

Step b:

A silicon oxide film was formed as an interlayer
insulation layer 161 to a thickness of 1.0 micrometer by
20 RF sputtering (Fig. 17B).

Step c:

A photoresist pattern was prepared for producing
contact holes 162 in the silicon oxide film deposited in
Step b, which contact holes 162 were then actually
25 formed by etching the interlayer insulation layer 161,
using the photoresist pattern for a mask (Fig. 17C).
RIE (Reactive Ion Etching) using CF_4 and H_2 gas was

1 employed for the etching operation.

Step d:

Thereafter, a pattern of photoresist (RD-2000N-41:
available from Hitachi Chemical Co., Ltd.) was formed for
5 pairs of device electrodes 5 and 6 and gaps L1
separating the respective pairs of electrodes and then
Ti and Ni were sequentially deposited thereon
respectively to thicknesses of 5.0 nm and 100 nm by
vacuum deposition. The photoresist pattern was
10 dissolved by an organic solvent and the Ni/Ti deposit
film was treated by using a lift-off technique to produce
pairs of device electrodes 5 and 6, each pair having a
width of 300 micrometers and separated from each other
by a distance L1 of 20 micrometers (Fig. 17D).

15 Step e:

After forming a photoresist pattern on the
device electrodes 5, 6 for upper wirings 93, Ti and Au
were sequentially deposited by vacuum deposition to
respective thicknesses of 5.0 nm and 500 nm and then
20 unnecessary areas were removed by means of a lift-off
technique to produce upper wirings 93 having a desired
profile (Fig. 17E).

Step f:

Electroconductive films 2 made of a mixture of
25 Sn and SnO_2 were produced by sputtering Sn in an oxygen
atmosphere, using a metal mask that had an opening for
the gap L1 separating the device electrodes and its

1 vicinity of each device (Fig. 17F). The width of the
electroconductive film 2 was 100 micrometers for this
example. The formed electroconductive films 2 were
made of fine particles containing SnO_2 as a principal
5 ingredient and had a film thickness of 70 angstroms and
an electric resistance per unit area of $2.5 \times 10^4 \Omega/\square$.
Note that the term "a fine particle film" as used
herein refers to a thin film constituted of a large
number of fine particles that may be loosely dispersed,
10 tightly arranged or mutually and randomly overlapping
(to form an island structure under certain conditions).
The diameter of fine particles to be used for the
purpose of the present invention is that of recognizable
fine particles arranged in any of the above described
15 states.

Step g:

The Cr film 171 and the baked electroconductive
film 2 were etched by using an acidic etchant to produce
a desired pattern (Fig. 18G).

20 Step h:

Then, a pattern for applying photoresist to the
entire surface area except the contact holes 162 was
prepared and Ti and Au were sequentially deposited by
vacuum deposition to respective thicknesses of 5.0 nm
25 and 500 nm. Any unnecessary areas were removed by
means of a lift-off technique to consequently bury
the contact holes 162 (Fig. 18H).

1 Now, lower wirings 92, an interlayer insulation
layer 161, upper wirings 93, and devices comprising
pairs of device electrodes 5 and 6 and electroconductive
films 2 were produced on the substrate 91.

5 Then, an electron source comprising the above
electron source substrate and an image-forming apparatus
incorporating such an electron source were prepared.
This will be described below by referring to Figs. 10, ~
11A and 11B.

10 The substrate 91 carrying thereon a large number
of devices prepared in a manner as described above was
rigidly fitted to a rear plate 101 and thereafter a
face plate 106 (prepared by forming a fluorescent film
104 and a metal back 105 on a glass substrate 103) was
15 arranged 5 mm above the substrate 91 by interposing a
support frame 102 therebetween. Frit glass was applied
to junction areas of the face plate 106, the support
frame 102 and the rear plate 101, which were then baked
at 400°C for 10 minutes or more in the atmosphere and
20 bonded together to a hermetically sealed condition
(Fig. 10).

 The substrate 91 was also firmly bonded to the
rear plate 101 by means of frit glass.

 In Fig. 10, reference numerals 92 and 93
25 respectively denote X- and Y-directional wirings.

 While the fluorescent film 104 may be solely
made of fluorescent bodies if the image-forming apparatus

1 is for black and white pictures, firstly black stripes
were arranged and then the gaps separating the black
stripes were filled with respective fluorescent bodies
' for primary colors to produce a fluorescent film 104
5 for this example (Fig. 11A).

The black stripes were made of a popular
material containing graphite as a principal ingredient.

The fluorescent bodies were applied to the glass
substrate 103 by using a slurry method. A metal back
10 105 is normally arranged on the inner surface of the
fluorescent film 104. In this example, a metal back
was prepared by producing an Al film by vacuum
deposition on the inner surface of the fluorescent film
104 that had been smoothed in a so-called electric
15 filming process.

The face plate 106 may be additionally provided
with transparent electrodes (not shown) arranged close
to the outer surface of the fluorescent film 104 in
order to improve the conductivity of the fluorescent
20 film 104, no such electrodes were used in this example
because the metal back proved to be sufficiently
conductive.

The fluorescent bodies were carefully aligned
with the respective devices before the above described
25 bonding operation.

The prepared glass container was then evacuated
by means of an exhaust pipe (not shown) and an exhaust

1 pump to achieve a sufficient degree of vacuum inside
the container. Thereafter, the electroconductive
film 2 of each of the devices arranged on the substrate
91 was subjected to an electric forming operation,
5 where a voltage was applied to the device electrodes 5,
6 of the devices by way of the external terminals Dox1
through Doxm and Doyl through Doyn to produce an
electron-emitting region 3 in each electroconductive
film 2.

10 The voltage used in the forming operation had a
waveform same as the one shown in Fig. 5B.

Referring to Fig. 5B, T1 and T2 were
respectively 1 milliseconds and 10 milliseconds and the
electric forming operation was carried out in vacuum of
15 a degree of approximately 1×10^{-6} torr. The wave
height (the peak voltage for the forming operation) of
the applied pulse voltage was increased stepwise with
steps of 0.1 V. During the electric forming operation,
an additional pulse voltage of 0.1 V was inserted in
20 each interval of T2 for measuring the resistance and the
application of pulse voltages was terminated to
complete the electric forming process when the
resistance measured by using a pulsed voltage exceeded
about 1 M Ω .

25 The forming voltage Vform for the above devices
was approximately 4.0 V.

Fine particles containing SnOx as a principal

1 ingredient and having an average diameter of 4.0 nm
were observed to be dispersed throughout the electron
emitting regions 3 of the electron-emitting devices
procuded in a manner as described above.

5 Subsequently, a protective film forming operation
was conducted on each of the devices under a vacuum
condition same as that of the electric forming process,
where a pulse voltage as shown in Fig. 5A was applied
to the device electrodes 5 and 6 of the electron-emitting
10 devices 94 through the external electrodes Dox1 through
Doxm and Doyl through Doyn.

In this operation, a pulse voltage having a
wave height value of 14 V was applied to the device
electrodes 5, 6 of the devices in order to cause them
15 emit electrons, while observing the emission current I_e .
The emission current I_e became saturated in approximately
30 minutes, when the protective film forming operation
was terminated.

All the devices were then subjected to a
20 chemical reduction process.

In this operation, nitrogen gas containing
hydrogen by 2% was introduced through a reducing gas
inlet pipe (not shown) under the control of a mass flow
controller (not shown) until it showed a partial pressure
25 of 1 millitorr in the vacuum apparatus.

As the devices were exposed to this atmosphere
for an hour, the electroconductive films 4 of the devices

1 containing SnO_2 as a principal ingredient were
chemically reduced to become so many films of fine
Sn particles that showed an electric resistance per
unit area of $6 \times 10^2 \Omega/\square$ or a value smaller than the
5 resistance before the chemical reduction by two digits.

Thus, the operation of preparing electron-
emitting devices 94 were completed as they had been
subjected to an electric forming operation, a protective
film forming operation and a chemical reduction process
10 to produce electron emitting regions 3.

Thereafter, the enclosure was evacuated to a
degree of vacuum of approximately 10^{-6} torr and then
hermetically sealed by melting and closing the exhaust
pipe (not shown) by means of a gas burner.

15 The apparatus was subjected to a getter process
using a high frequency heating technique in order to
maintain the degree of vacuum in the apparatus after the
sealing operation, where an getter disposed at a
predetermined position (not shown) in the enclosure was
20 heated by high frequency heating immediately before the
sealing operation to form a film as a result of vapor
deposition. The getter is a material containing Ba as
a principal component.

The electron-emitting devices of the above
25 image-forming apparatus were then caused to emit
electrons by applying scanning signals and modulation
signals generated by a signal generating means (not

1 shown) thereto through the external terminals Dox1
through Doxm and Doyl through Doyn and the emitted
electrons were accelerated by applying a high voltage
of greater than several kV to the metal back 105 or a
5 transparent electrode (not shown) via the high voltage
terminal Hv so that they collides with the fluorescent
film 104 until the latter was energized to emit light
and produce images.

The electron source prepared for this example
10 consumed little power with a reduced drive voltage so
that the load applied to the circuits that are
peripheral to the electron source was also reduced.
Consequently the image-forming apparatus incorporating
such an electron source was prepared at low cost.

15 The image-forming apparatus operated stably with
a reduced power consumption rate to display excellent
images.

(Example 6)

This example deals with an image-forming
20 apparatus comprising a large number of surface conduction
electron-emitting devices and control electrodes (grids).

Since an apparatus to be dealt in this example
can be prepared in a way as described above concerning
the image-forming apparatus of Example 5, the method of
25 manufacturing the same will not be described any
further.

Each of the surface conduction electron-emitting

1 devices of the device electrode had a gap of 50
micrometers between the device electrodes. A
chemical reduction process was conducted on the devices
in a manner similar to the one described earlier for
5 Example 5. In this reduction process, the devices
were exposed to nitrogen gas containing hydrogen by 2%
and having a partial pressure of 100 mtorr for 30
minutes.

The configuration of the apparatus will be
10 described in terms of the electron source of the
apparatus prepared by arranging a number of surface
conduction electron-emitting devices.

Fig. 13B shows a schematic plan view the
electron source which is a ladder type. Referring to
15 Fig. 13B, 144 denotes an electron source substrate
typically made of soda lime glass and 131 denotes an
surface conduction electron-emitting device arranged on
the substrate 144 and shown in a dotted circle.
Whereas Dx'1 through Dx'6 that are commonly indicated
20 by 132 denote common wirings for the surface conduction
electron-emitting devices.

The surface conduction electron-emitting
devices 131 were arranged in rows running along X-
direction (hereinafter referred to as device rows) and
25 the surface conduction electron-emitting devices of
each row are connected in parallel by a pair of common
wirings running along the rows. Note that a single

1 common wiring is arranged between any two adjacent
device rows to serve for the both rows as a wiring
electrode. For instance, common wiring or wiring
electrode Dx'2 serves for both the first device row
5 and the second device row.

This arrangement of wiring electrodes is
advantageous in that, if compared with the arrangement
of Fig. 13A, the space separating any two adjacent
rows of surface conduction electron-emitting devices
10 can be significantly reduced in Y-direction.

In the apparatus of this example comprising the
above described electron source, the electron source
can drive any device rows independently by applying an
appropriate drive voltage to the related wiring
15 electrodes. More specifically, a voltage exceeding the
threshold voltage level for electron emission is applied
to the device rows to be driven to emit electrons,
whereas a voltage not exceeding the threshold voltage
level for electron emission (e.g., 0 V) is applied to
20 the remaining device rows. (A voltage exceeding the
threshold voltage level and used for the purpose of the
invention is expressed by drive voltage $V_{ope}[V]$
hereinafter.)

For instance, only the devices of the third row
25 can be driven to operate by applying 0[V] to the wiring
electrodes Dx'1 through Dx'3 and $V_{ope}[V]$ to the wiring
electrodes Dx'4 through Dx'6. Consequently,

1 Vo_{pe}-0 = Vo_{pe}[V] is applied to the devices of the
third row, whereas 0[V], 0-0 = 0[V] or Vo_{pe}-Vo_{pe} = 0[V],
is applied to all the devices of the remaining rows.

5 Likewise, the devices of the second and the
fifth rows can be driven to operate simultaneously by
applying 0[V] to the wiring electrodes Dx'1, Dx'2 and
Dx'6 and Vo_{pe}[V] to the wiring electrodes Dx'3, Dx'4 and
Dx'5. In this way, the devices of any device row of this
electron source can be driven selectively.

10 While each device row has twelve (12) surface
conduction electron-emitting devices arranged along the
X-direction in the electron sources of Fig. 13B, the
number of devices to be arranged in a device row is not
limited thereto and a greater number of devices may
15 alternatively be arranged. Additionally, while there
are five (5) device rows in the electron source, the
number of device rows is not limited thereto and a
greater number of device rows may alternatively be
arranged.

20 Now, a panel type CRT incorporating an electron
source of the above described type will be described.

Fig. 14 is a schematic perspective view of a
panel type CRT incorporating an electron source as
illustrated in Fig. 13B. In Fig. 14, VC denote a glass
25 vacuum container provided with a face plate for
displaying images as a component thereof. A transparent
electrode made of ITO is arranged on the inner surface of

1 the face plate and red, green and blue fluorescent
members are applied onto the transparent electrode in
the form of a mosaic or stripes without interfering
with each other. To simplify the illustration, the
5 transparent electrodes and the fluorescent members are
collectively indicated by reference symbol 104 in Fig.
14. Black stripes known in the field of CRT may be
arranged to fill the blank areas of the transparent
electrode that are not occupied by the fluorescent
10 stripes. Similarly, a metal back layer of any known
type may be arranged on the fluorescent members. The
transparent electrode is electrically connected to the
outside of the vacuum container by way of a terminal
Hv so that an voltage may be applied thereto in order
15 to accelerate electron beams.

In Fig. 14, 144 denotes the substrate of the
electron source rigidly fitted to the bottom of the
vacuum container VC, on which a number of surface
conduction electron-emitting devices are arranged in
20 a manner as described above by referring to Fig. 13B.
The wiring electrodes of the device rows are
electrically connected to respective electrode terminals
Dox1 through Dox(m+1) arranged on a lateral panel of
the apparatus so that electric drive signals may be
25 applied thereto from outside of the vacuum enclosure
($m = 200$ for the apparatus of this example).

Stripe-shaped grid electrodes 140 are arranged

1 in the middle between the substrate 144 and the face
plate 106. There are provided a total of 200 grid
electrodes GR arranged in a direction perpendicular to
that of the device rows (or in the Y-direction) and
5 each grid electrode has a given number of openings 141
for allowing electron beams to pass therethrough. More
specifically, a circular opening 141 is provided for
each surface conduction electron-emitting device. The
grid electrodes are electrically connected to the
10 outside of the vacuum container via respective electric
terminals G1 through Gn ($n = 200$ for the apparatus of
this example).

The above described display panel comprises
surface conduction electron-emitting devices arranged
15 in 200 device rows and 200 grid electrodes to form an
X-Y matrix of 200×200 . With such an arrangement, an
image can be displayed on the screen on a line by line
basis by applying a modulation signal to the grid
electrodes for a single line of an image in synchronism
20 with the operation of driving (scanning) the surface
conduction electron-emitting devices on a row by row
basis to control the irradiation of electron beams onto
the fluorescent film.

Fig. 22 is a block diagram of an electric
25 circuit to be used for driving the display panel of the
above described electron source having a ladder-like
arrangement in order to display images according to TV

1 signals of the NTSC system. Pulse modulation was used
for the image-forming apparatus.

The electron-emitting devices of the above
image-forming apparatus were then caused to emit
5 electrons by applying scanning signals and modulation
signals generated by a signal generating means thereto
through the external terminals Dox1 through Dox(m+1)
and Doyl through Doyn and the emitted electrons were
accelerated by applying a high voltage of 10 kV to a
10 metal back (not shown) or a transparent electrode (not
shown) via the high voltage terminal Hv so that they
collides with the fluorescent film 104 until the latter
was energized to emit light and produce images.

The electron source prepared for this example
15 consumed little power with a reduced drive voltage so
that the load applied to the circuits that are
peripheral to the electron source was also reduced.
Consequently the image-forming apparatus incorporating
such an electron source was prepared at low cost.

20 (Example 7)

Contrary to Example 1 where the film of fine
PdO particles of an electron-emitting device was
chemically reduced by heating in vacuum, the film of
fine particles of the electron-emitting device of this
25 example was heated and reduced in a reducing solution.

The electron-emitting device having a
configuration as illustrated in Figs. 7A and 7B was

1 prepared by following Steps a through e, of which
Steps a through d are same as those of Example 1
above. So, only Step e will be described here.

As in the case of Example 1, the device
5 comprising a pair of device electrodes 5, 6 and an
electroconductive film 4 including an electron emitting
region 3 arranged on a substrate 1 was subjected to a
chemical reduction process as described below.

Step e:

10 As shown in Fig. 21, the electron-emitting
device was placed in a liquid of 100% formic acid
(reducing liquid) and heated to temperature between
50°C and 60°C for two minutes by means of a heater
which is connected to a temperature controller.

15 Consequently, the PdO in the form of a film of fine
particles of the device that has not undergone an
electric forming process was chemically reduced to
become metal Pd also in the form a film of fine
particles having an electric resistance per unit area
20 of $5 \times 10^2 \Omega/\square$ or a value smaller than the resistance
before the chemical reduction by two digits.

In an attempt to see the properties of the flat
type electron-emitting device prepared through the
preceding steps, it was observed for electron-emitting
25 performance, using a measuring system as illustrated in
Fig. 4. In the above observation, the distance H between
the anode 34 and the electron-emitting device was 4 mm

1 and the potential of the anode 34 was 1 kV, while the
degree of vacuum in the vacuum chamber of the system
was held to 1×10^{-6} torr throughout the gauging
operation.

5 A device voltage was applied between the device
electrodes 5, 6 of the device to see the device current
 I_f and the emission current I_e under that condition.
Fig. 6 shows the current-voltage relationships obtained
as a result of the observation.

10 The emission current I_e of the device began to
increase sharply when the device voltage (V_f) became as
high as 8 and a device current I_f of 2.0 millia and an
emission current I_e of 1.2 microA were observed when
the device voltage rose to 14 V to provide an electron
15 emission efficiency $\theta = I_e/I_f \times 100(\%)$ of 0.06%.

When the device was observed before the
chemical reduction process, the film of PdO fine
particles (electroconductive film) of the device showed
an electric resistance of 3.5 k Ω and the fissured area
20 had an electric resistance of 7 k Ω .

After the chemical reduction process, it was
found that the electric resistance of the film of PdO
fine particles of the electron-emitting device that
had undergone an chemical reduction process (the device
25 of this example) was as low as 30 Ω , which was negligible
when compared with that of the fissured area.

In other words, for an electron-emitting device

1 after a chemical reduction process according to the
invention to obtain the same electron emission rate
as a device before the process having required a device
voltage of 21 V, the device after the process required
5 a power consumption rate of only 28 milliW, whereas
it was 42 milliW for the device before the process,
i.e., the former being two thirds of the latter, thus
proving a significant saving of power.

Note that the duration of chemical reduction
10 process was as short as two hour or much shorter than
that of the device of Example 1, which was ten hours and
this fact can further contribute to raising the rate of
manufacturing electron-emitting devices of the type
under consideration. Additionally, since the chemical
15 reduction process does not require any gas nor vacuum
apparatus, the entire facility required for
manufacturing electron-emitting devices can be
remarkably simplified.

(Example 8)

20 Fig. 23 is a block diagram of the display
apparatus comprising an electron source realized by
arranging a number of surface conduction electron-
emitting devices and a display panel and designed to
display a variety of visual data as well as pictures of
25 television transmission in accordance with input
signals coming from different signal sources.

Referring to Fig. 23, the apparatus comprises

1 a display panel 500, a display panel drive circuit 501,
a display panel controller 502, a multiplexer 503, a
decoder 504, an input/output interface circuit 505, a
CPU 506, an image generation circuit 507, image memory
5 interface circuits 508, 509 and 510, an image input
interface circuit 511, TV signal receiving circuits
512 and 513 and an input section 514. If the display
apparatus is used for receiving television signals that
are constituted by video and audio signals, circuits,
10 speakers and other devices are required for receiving,
separating, reproducing, processing and storing audio
signals along with the circuits shown in the drawing.
However, such circuits and devices are omitted here in
view of the scope of the present invention.

15 Now, the components of the apparatus will be
described, following the flow of image data therethrough.

Firstly, the TV signal reception circuit 513 is
a circuit for receiving TV image signals transmitted via
a wireless transmission system using electromagnetic
20 waves and/or spatial optical telecommunication networks.

The TV signal system to be used is not limited to
a particular one and any system such as NTSC, PAL or
SECAM may feasibly be used with it. It is particularly
suited for TV signals involving a larger number of
25 scanning lines (typically of a high definition TV
system such as the MUSE system) because it can be used
for a large display panel comprising a large number of

1 pixels.

The TV signals received by the TV signal reception circuit 513 are forwarded to the decoder 504.

Secondly, the TV signal reception circuit 512 is a circuit for receiving TV image signals transmitted via a wired transmission system using coaxial cables and/or optical fibers. Like the TV signal reception circuit 513, the TV signal system to be used is not limited to a particular one and the TV signals received by the circuit are forwarded to the decoder 504.

The image input interface circuit 511 is a circuit for receiving image signals forwarded from an image input device such as a TV camera or an image pick-up scanner. It also forwards the received image signals to the decoder 504.

The image memory interface circuit 510 is a circuit for retrieving image signals stored in a video tape recorder (hereinafter referred to as VTR) and the retrieved image signals are also forwarded to the decoder 504.

The image memory interface circuit 509 is a circuit for retrieving image signals stored in a video disc and the retrieved image signals are also forwarded to the decoder 504.

The image memory interface circuit 508 is a circuit for retrieving image signals stored in a device for storing still image data such as so-called still

1 disc and the retrieved image signals are also forwarded
to the decoder 504.

The input/output interface circuit 505 is a
circuit for connecting the display apparatus and an
5 external output signal source such as a computer, a
computer network or a printer. It carries out input/
output operations for image data and data on characters
and graphics and, if appropriate, for control signals
and numerical data between the CPU 506 of the display
10 apparatus and an external output signal source.

The image generation circuit 507 is a circuit
for generating image data to be displayed on the display
screen on the basis of the image data and the data on
characters and graphics input from an external output
15 signal source via the input/output interface circuit
505 or those coming from the CPU 506. The circuit
comprises reloadable memories for storing image data and
data on characters and graphics, read-only memories for
storing image patterns corresponding given character
20 codes, a processor for processing image data and other
circuit components necessary for the generation of
screen images.

Image data generated by the circuit for display
are sent to the decoder 504 and, if appropriate, they
25 may also be sent to an external circuit such as a
computer network or a printer via the input/output
interface circuit 505.

1 The CPU 506 controls the display apparatus and
carries out the operation of generating, selecting and
editing images to be displayed on the display screen.
For example, the CPU 506 sends control signals to the
5 multiplexer 503 and appropriately selects or combines
signals for images to be displayed on the display
screen.

At the same time it generates control signals
for the display panel controller 502 and controls the
10 operation of the display apparatus in terms of image
display frequency, scanning method (e.g., interlaced
scanning or non-interlaced scanning), the number of
scanning lines per frame and so on.

The CPU 506 also sends out image data and data
15 on characters and graphic directly to the image
generation circuit 507 and accesses external computers
and memories via the input/output interface circuit
505 to obtain external image data and data on
characters and graphics.

20 The CPU 506 may additionally be so designed as
to participate other operations of the display apparatus
including the operation of generating and processing
data like the CPU of a personal computer or a word
processor. The CPU 506 may also be connected to an
25 external computer network via the input/output interface
circuit 505 to carry out numerical computations and
other operations, cooperating therewith.

1 The input section 514 is used for forwarding the
instructions, programs and data given to it by the
operator to the CPU 506. As a matter of fact, it may
be selected from a variety of input devices such as
5 keyboards, mice, joy sticks, bar code readers and voice
recognition devices as well as any combinations thereof.

 The decoder 504 is a circuit for converting
various image signals input via said circuits 507
through 513 back into signals for three primary colors,
10 luminance signals and I and Q signals. Preferably, the
decoder 504 comprises image memories as indicated by a
dotted line in Fig. 23 for dealing with television
signals such as those of the MUSE system that require
image memories for signal conversion.

15 The provision of image memories additionally
facilitates the display of still images as well as such
operations as thinning out, interpolating, enlarging,
reducing, synthesizing and editing frames to be
optionally carried out by the decoder 504 in
20 cooperation with the image generation circuit 507 and
the CPU 506.

 The multiplexer 503 is used to appropriately
select images to be displayed on the display screen
according to control signals given by the CPU 506.
25 In other words, the multiplexer 503 selects certain
converted image signals coming from the decoder 504
and sends them to the drive circuit 501. It can also

1 divide the display screen in a plurality of frames to
display different images simultaneously by switching
from a set of image signals to a different set of
image signals within the time period for displaying a
5 single frame.

The display panel controller 502 is a circuit
for controlling the operation of the drive circuit 501
according to control signals transmitted from the CPU
506. Among others, it operates to transmit signals to
10 the drive circuit 501 for controlling the sequence of
operations of the power source (not shown) for driving
the display panel in order to define the basis operation
of the display panel.

It also transmits signals to the drive circuit
15 501 for controlling the image display frequency and the
scanning method (e.g., interlaced scanning or non-
interlaced scanning) in order to define the mode of
driving the display panel.

If appropriate, it also transmits signals to the
20 drive circuit 501 for controlling the quality of the
images to be displayed on the display screen in terms
of luminance, contrast, color tone and sharpness.

The drive circuit 501 is a circuit for generating
drive signals to be applied to the display panel 500.
25 It operates according to image signals coming from said
multiplexer 503 and control signals coming from the
display panel controller 502.

1 A display apparatus according to the invention
and having a configuration as described above and
illustrated in Fig. 23 can display on the display panel
500 various images given from a variety of image data
5 sources.

More specifically, image signals such as
television image signals are converted back by the
decoder 504 and then selected by the multiplexer 503
before sent to the drive circuit 501. On the other
10 hand, the display controller 502 generates control
signals for controlling the operation of the drive
circuit 501 according to the image signals for the
images to be displayed on the display panel 500.

The drive circuit 501 then applies drive signals
15 to the display panel 500 according to the image signals
and the control signals. Thus, images are displayed
on the display panel 500.

All the above described operations are
controlled by the CPU 506 in a coordinated manner.

20 The above described display apparatus can not
only select and display particular images out of a
number of images given to it but also carry out various
image processing operations including those for
enlarging, reducing, rotating, emphasizing edges of,
25 thinning out, interpolating, changing colors of and
modifying the aspect ratio of images and editing
operations including those for synthesizing, erasing,

1 connecting, replacing and inserting images as the image
memories incorporated in the decoder 504, the image
generation circuit 507 and the CPU 506 participate such
operations.

5 Although not described with respect to the above
embodiment, it is possible to provide it with additional
circuits exclusively dedicated to audio signal processing
and editing operations.

Thus, a display apparatus according to the
10 invention and having a configuration as described above
can have a wide variety of industrial and commercial
applications because it can operate as a display
apparatus for television broadcasting, as a terminal
apparatus for video teleconferencing, as an editing
15 apparatus for still and movie pictures, as a terminal
apparatus for a computer system, as an OA apparatus such
as a word processor, as a game machine and in many other
ways.

It may be needless to say that Fig. 23 shows only
20 an example of possible configuration of a display
apparatus comprising a display panel provided with an
electron source prepared by arranging a number of surface
conduction electron-emitting devices and the present
invention is not limited thereto. For example, some of
25 the circuit components of Fig. 23 may be omitted or
additional components may be arranged there depending
on the application.

1 For instance, if a display apparatus according
to the invention is used for visual telephone, it may
be appropriately made to comprise additional components
such as a television camera, a microphone, lighting
5 equipment and transmission/reception circuits including
a modem.

 Since a display apparatus according to the
invention comprises a display panel that is provided
with an electron source prepared by arranging a large
10 number of surface conduction electron-emitting device
and hence adaptable to reduction in the depth, the
overall apparatus can be made very thin.

 Additionally, since a display panel comprising
an electron source prepared by arranging a large number
15 of surface conduction electron-emitting devices is
adapted to have a large display screen with an enhanced
luminance and provide a wide angle for viewing, it can
offer really impressive scenes to the viewers with a
sense of presence.

20 [Advantages of the Invention]

 As described in detail above, the present
invention make it possible to reduce the drive voltage
and the power consumption rate of an electron-emitting
device and hence provide an energy saving electron
25 source and a high quality image-forming apparatus
incorporating such an electron source.

 Additionally, according to the invention, since

1 it is now possible to provide a large gap between the
device electrodes of an electron-emitting device
without significantly consuming power, electron-
emitting devices can be manufactured on a mass
5 production basis without particularly paying attention
to the precision of printing operations.

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1 WHAT IS CLAIMED IS:

1. A method of manufacturing an electron-emitting device comprising a pair of oppositely disposed electrodes and an electroconductive film inclusive of an electron-emitting region arranged between said electrodes characterized in that said method comprises a processing step of reducing the electric resistance of the electroconductive film arranged between the electrodes.

10

2. A method of manufacturing an electron-emitting device according to claim 1, wherein said electroconductive film arranged between said electrodes mainly contains one or more oxides before the reducing step and one or more metals after the reducing step.

3. A method of manufacturing an electron-emitting device according to claim 1, wherein said electroconductive film is made of at least an oxide selected from PdO, SnO₂, In₂O₃, PbO, MoO and MoO₂ or a mixture of a metal selected from Pd, Ru, Ag, Ti, In, Cu, Cr, Fe, Zn, Sn, W and Pb and said oxide or oxides.

4. A method of manufacturing an electron-emitting device according to claim 1, wherein said processing step of reducing the electric resistance of the electroconductive film arranged between the electrodes

25

1 is a step of chemically reducing the electroconductive
film.

5 5. A method of manufacturing an electron-
emitting device according to claim 4, wherein said
chemical reduction step includes a step of heating said
electroconductive film in vacuum.

10 6. A method of manufacturing an electron-
emitting device according to claim 4, wherein said
chemical reduction step includes a step of heating said
electroconductive film in an atmosphere of reducing gas.

15 7. A method of manufacturing an electron-
emitting device according to claim 6, wherein said
reducing gas contains hydrogen.

20 8. A method of manufacturing an electron-
emitting device according to claim 4, wherein said
chemical reduction step includes a step of dipping said
electroconductive film in a reducing solution.

25 9. A method of manufacturing an electron-
emitting device according to claim 8, wherein said
reducing solution contains formic acid.

10. A method of manufacturing an electron-

1 emitting device according to one of claims 1 through 9,
wherein said processing step of reducing the electric
resistance of said electroconductive film arranged
between said electrodes is conducted after a step of
5 producing a high resistance area in said electroconductive
film arranged between said electrodes.

11. A method of manufacturing an electron-
emitting device according to claim 10, wherein said step
10 of producing a high resistance area in said
electroconductive film includes a step of electrically
forming said electroconductive film arranged between
said electrodes.

15 12. A method of manufacturing an electron-
emitting device according to one of claims 1 through
9, wherein it further comprises a step of depositing
carbon or a carbon compounds on said electroconductive
film.

20

13. A method of manufacturing an electron-
emitting device according to claim 12, wherein said step
of reducing the electric resistance of said
electroconductive film arranged between said electrodes
25 is conducted after said step of depositing carbon or a
carbon compounds on said electroconductive film.

1 14. A method of manufacturing an electron-
emitting device according to claim 12, wherein said
step of depositing carbon or a carbon compounds on
said electroconductive film includes a step of applying
5 in an atmosphere of the carbon compounds a voltage to
said electroconductive film arranged between said
electrodes.

10 15. An electron source comprising an electron-
emitting device for emitting electrons in accordance
with input signals characterized in that said electron-
emitting device is produced by a manufacturing method
according to one of claims 1 through 9.

15 16. An electron source comprising a plurality
of rows of electron-emitting devices having respective
pairs of terminals connected to common wirings and a
modulation means for modulating electron beams emitted
from said electron-emitting devices in accordance with
20 input signals characterized in that said electron-
emitting devices are produced by a manufacturing method
according to one of claims 1 through 9.

25 17. An electron source comprising a plurality
of electron-emitting devices for emitting electron beams
in accordance with input signals, said electron-emitting
devices being connected respectively to m X-directional

1 wirings and n Y-directional wirings, said wiring being
electrically insulated from one another, characterized
in that said electron-emitting devices are produced by
a manufacturing method according to one of claims 1
5 through 9.

18. An image-forming apparatus comprising an
electron source and an image-forming member for forming
images in accordance with input signals characterized
10 in that said electron source is an electron source
according to claim 15.

19. An image-forming apparatus according to
claim 18, wherein said image-forming member comprises
15 a fluorescent body.

20. An image-forming apparatus comprising an
electron source and an image-forming member for forming
images in accordance with input signals characterized
20 in that said electron source is an electron source
according to claim 16.

21. An image-forming apparatus according to
claim 20, wherein said image-forming member comprises a
25 fluorescent body.

22. An image-forming apparatus comprising

1 an electron source and an image-forming member for
forming images in accordance with input signals
characterized in that said electron source is an
electron source according to claim 17.

5

23. An image-forming apparatus according to
claim 22, wherein said image-forming member comprises
a fluorescent body.

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ABSTRACT OF THE DISCLOSURE

An electron-emitting device comprises a pair of oppositely disposed electrodes and an electroconductive film inclusive of an electron-emitting region, arranged between the electrodes. The electric resistance of the electroconductive film is reduced after forming the electron-emitting region in the course of manufacturing the electron-emitting device.

FIG. 1A

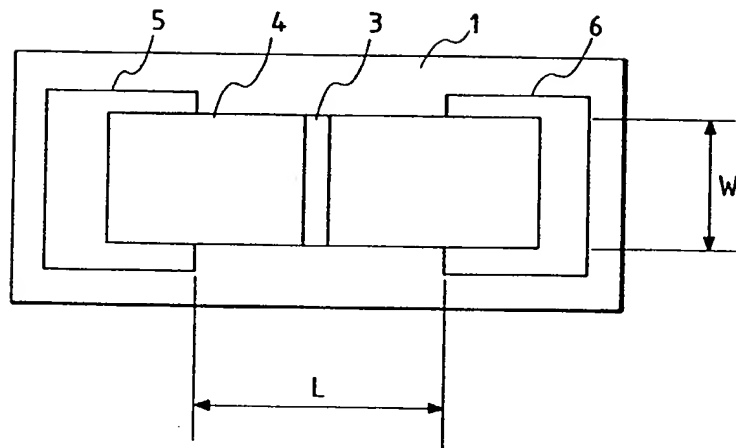


FIG. 1B

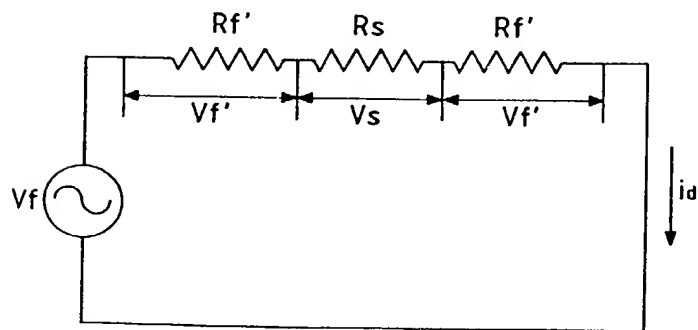


FIG. 2

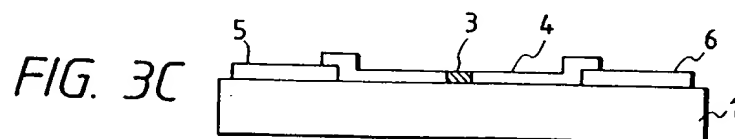
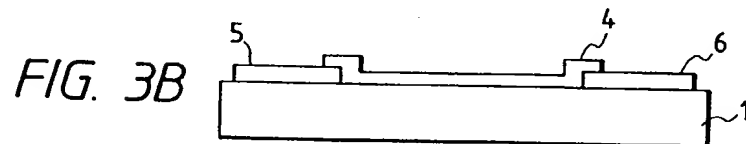
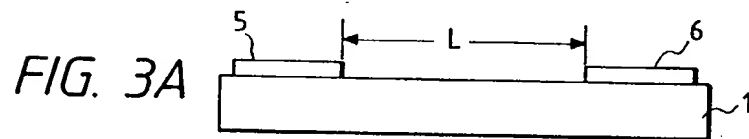
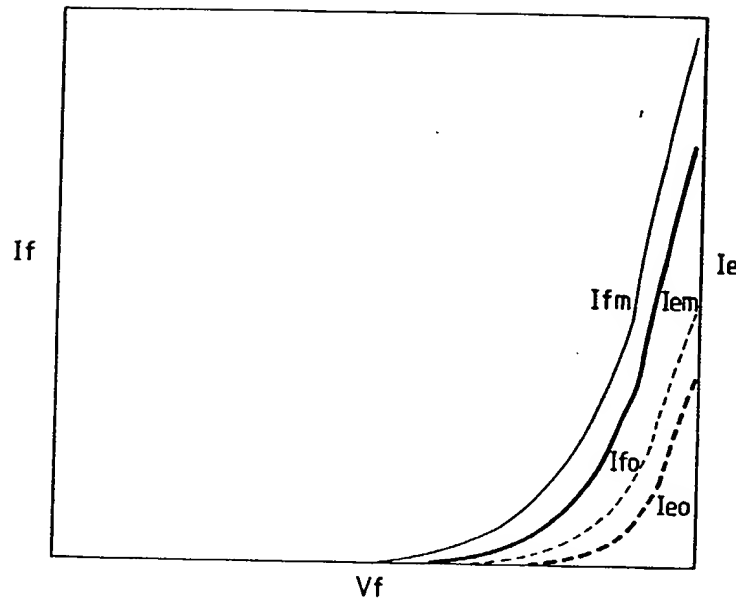


FIG. 4

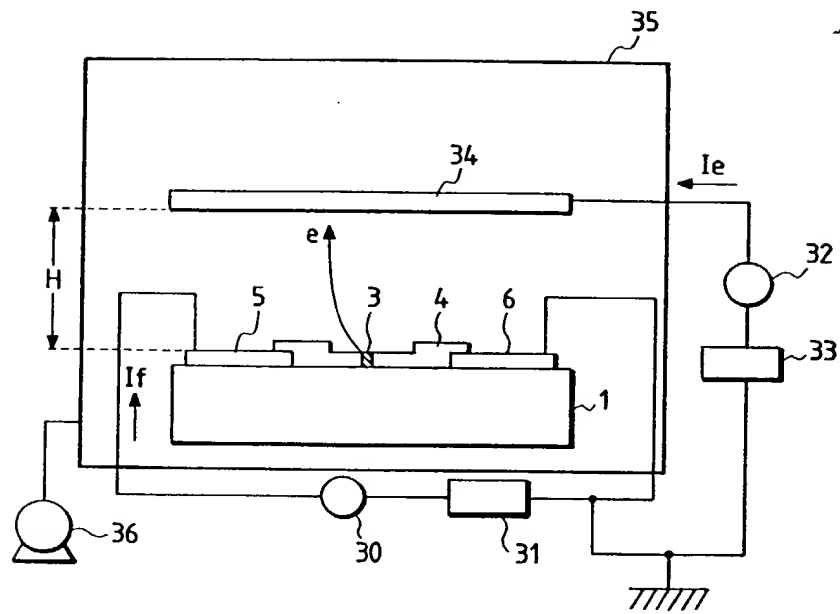


FIG. 5A

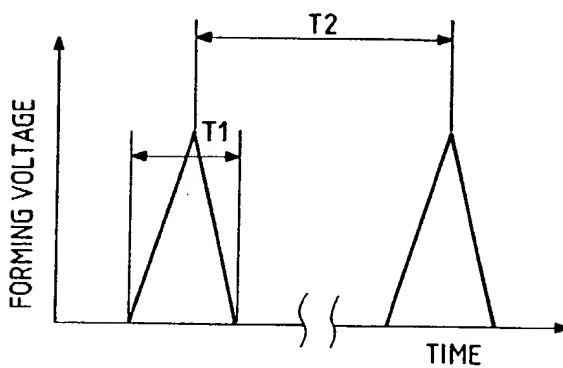


FIG. 5B

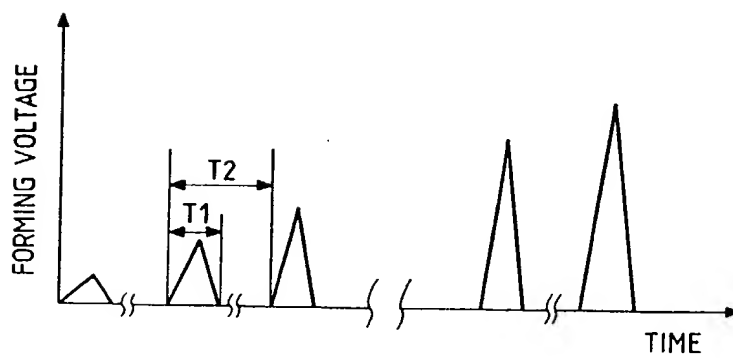


FIG. 6

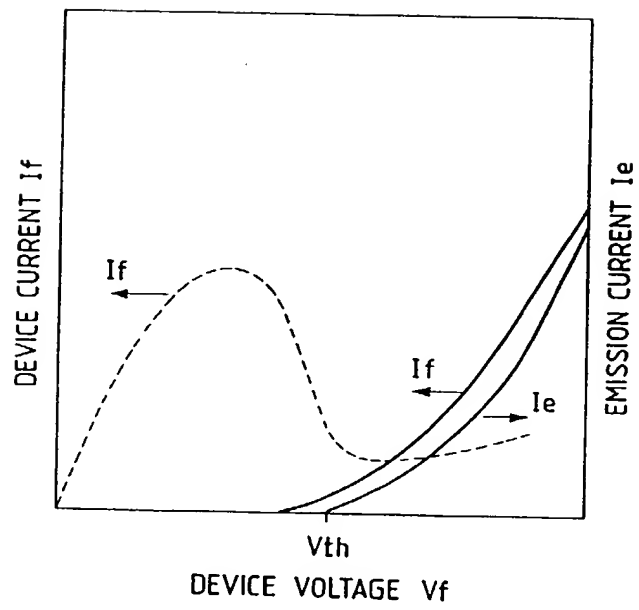


FIG. 7A

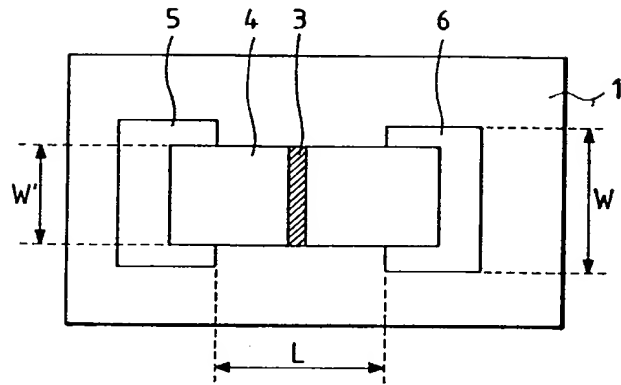


FIG. 7B

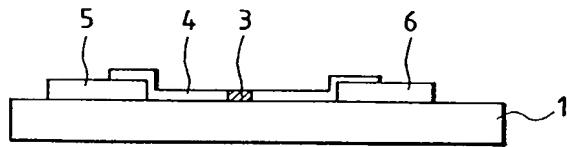


FIG. 8

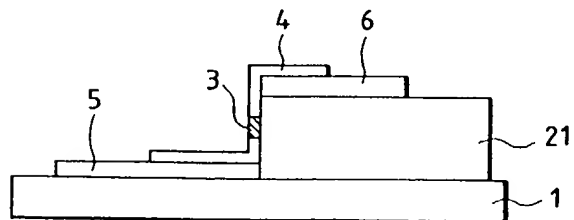


FIG. 9

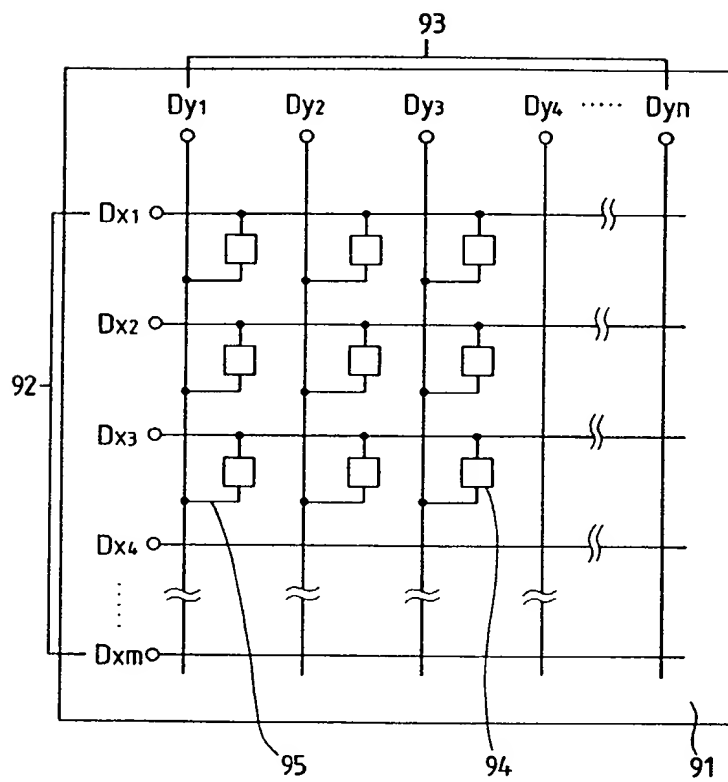


FIG. 10 SIMPLE MATRIX

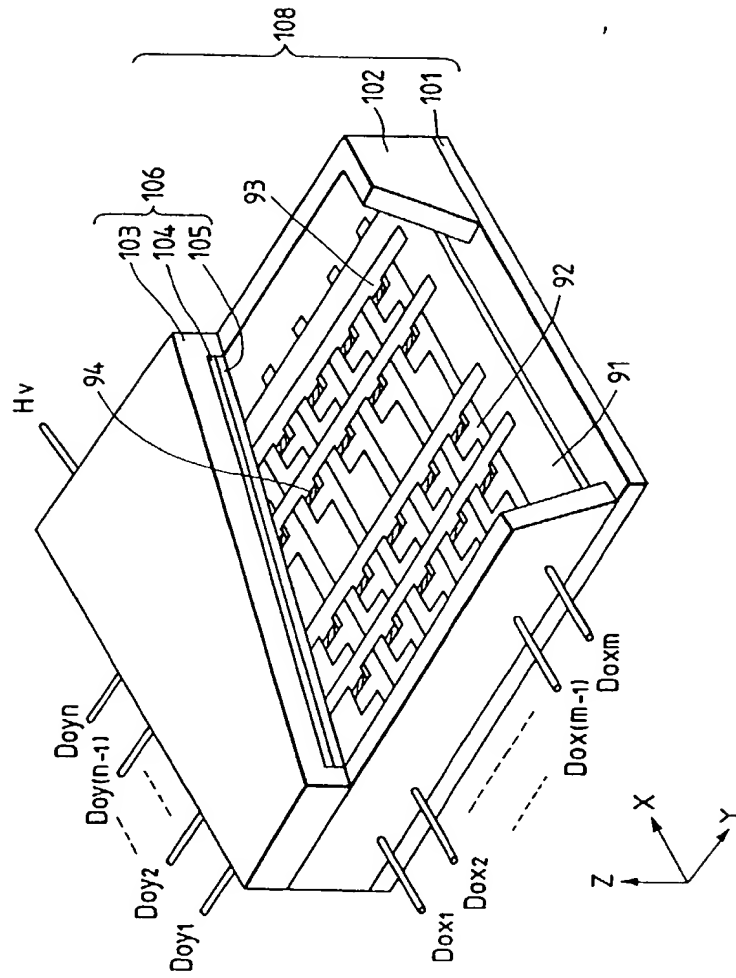


FIG. 11A

STRIPE

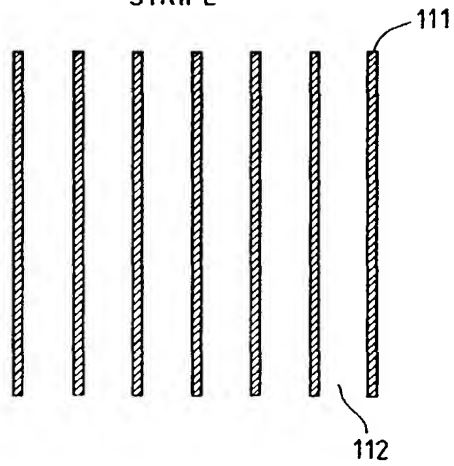


FIG. 11B

MATRIX

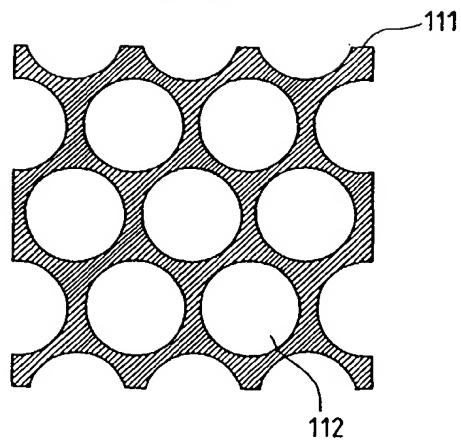


FIG. 12

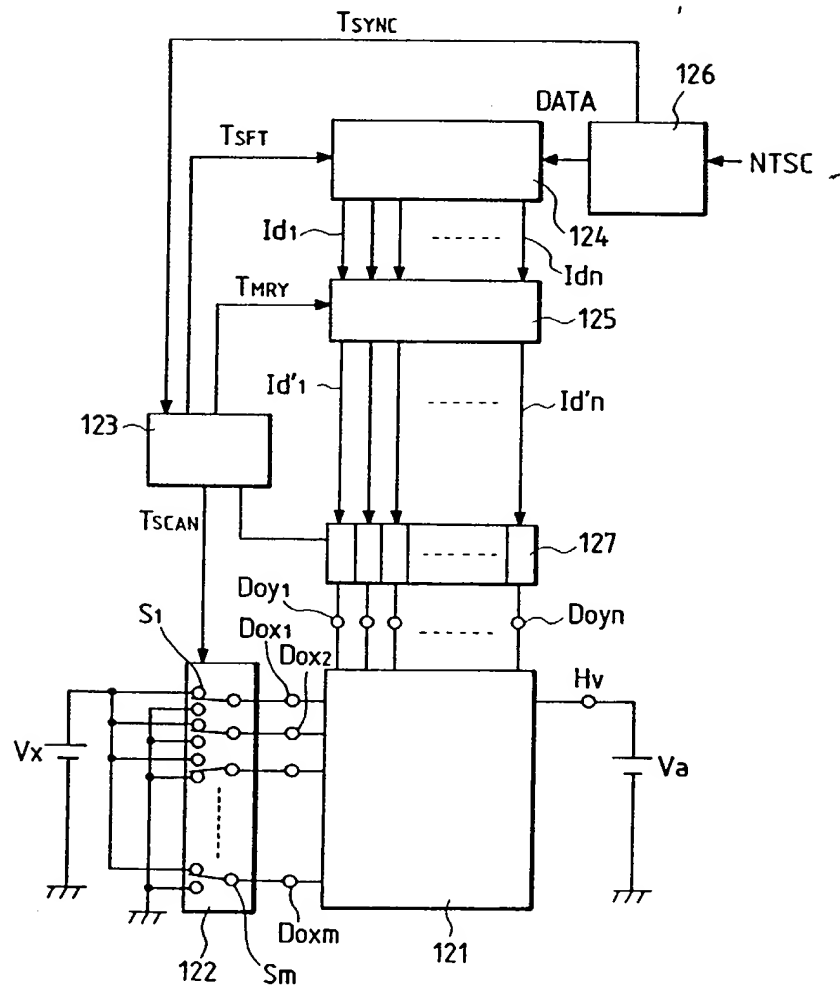


FIG. 13A

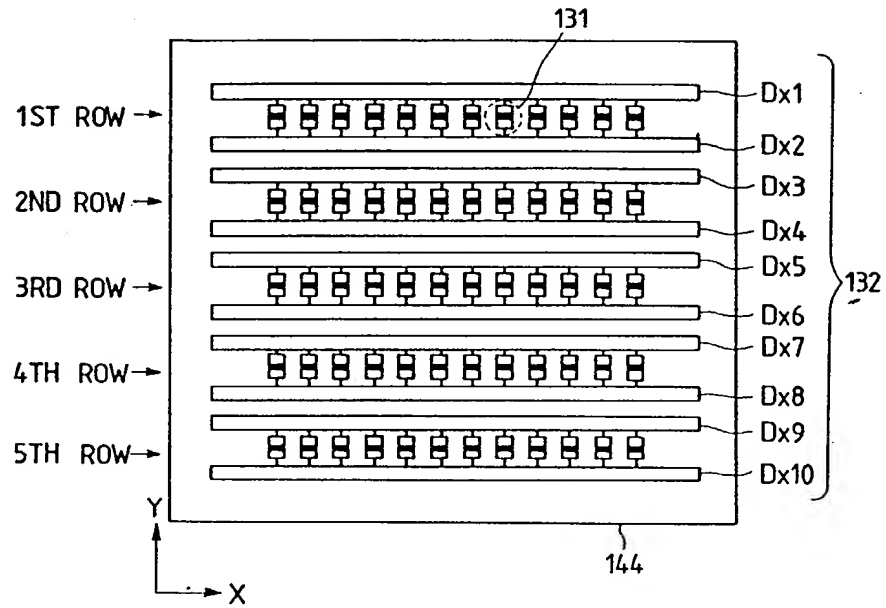


FIG. 13B

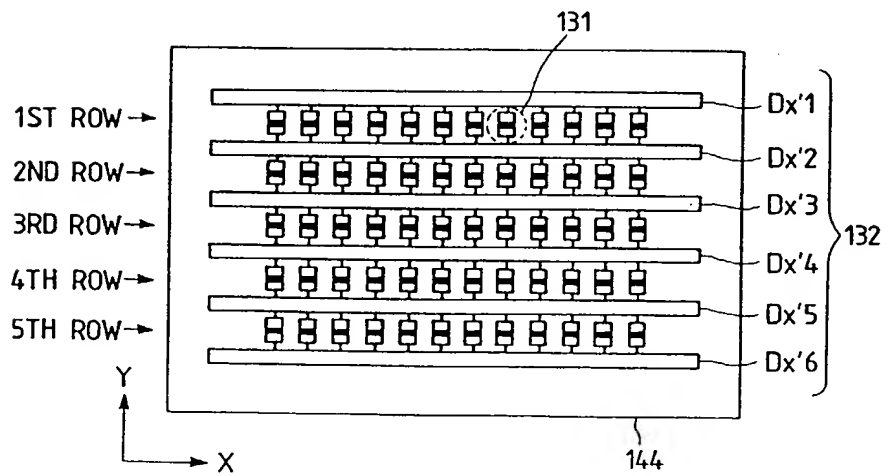


FIG. 14

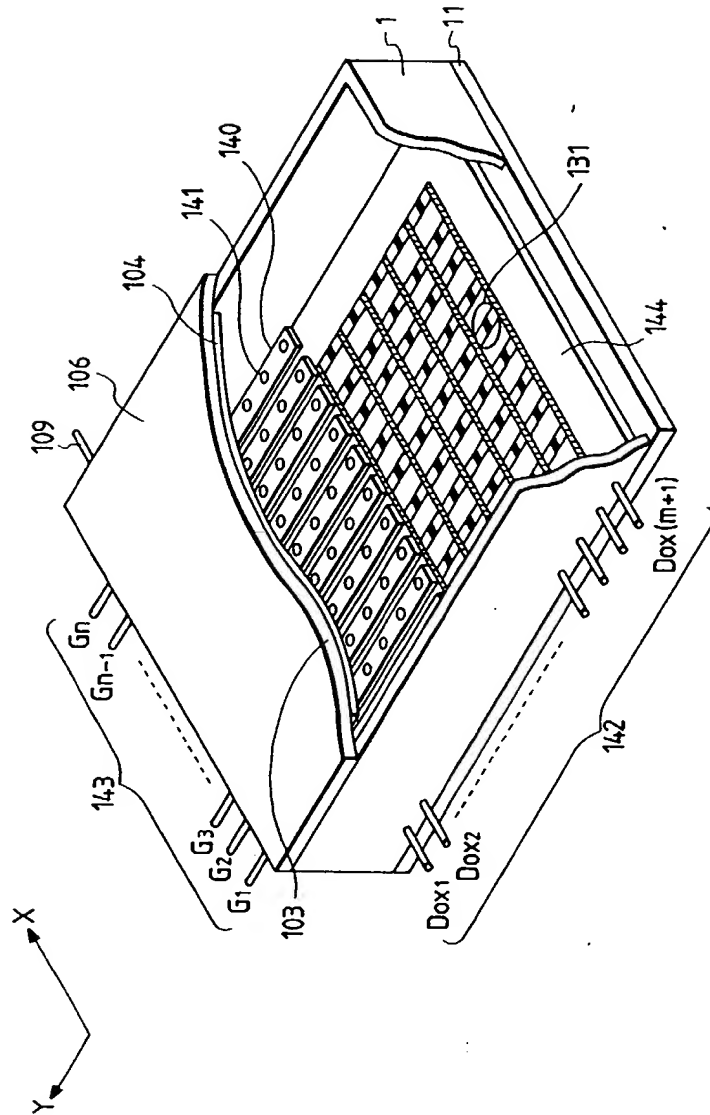


FIG. 15

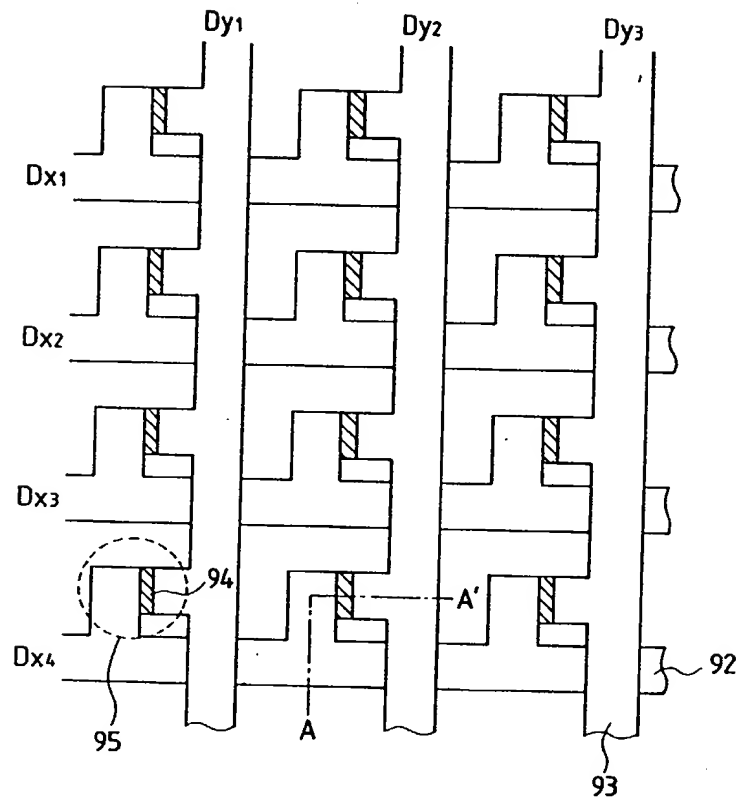
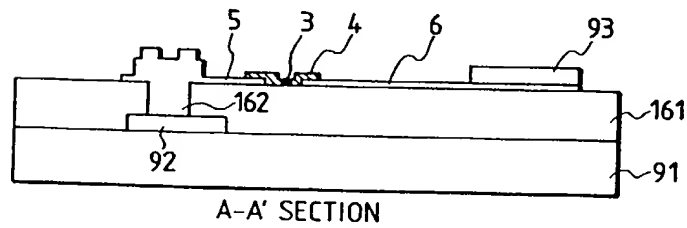


FIG. 16



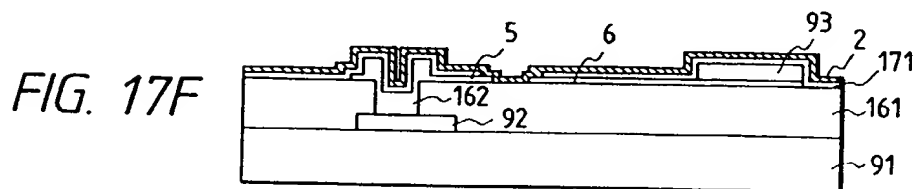
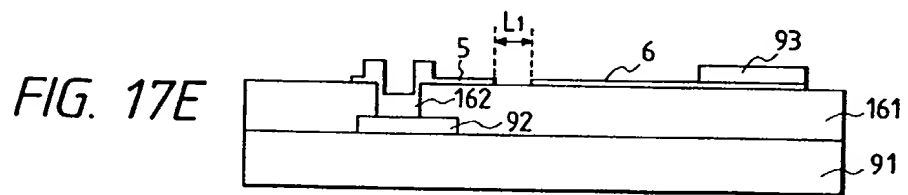
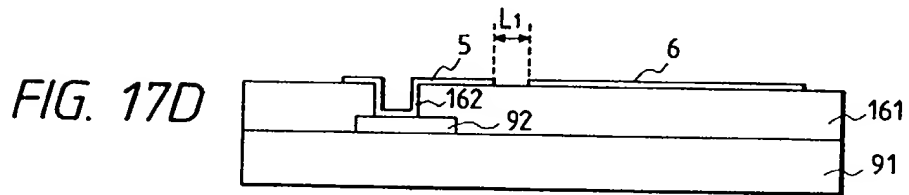
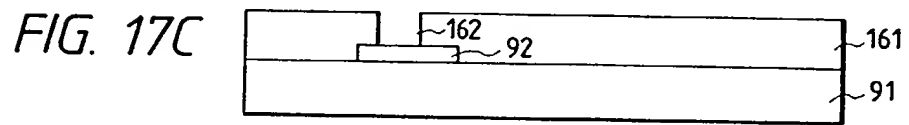
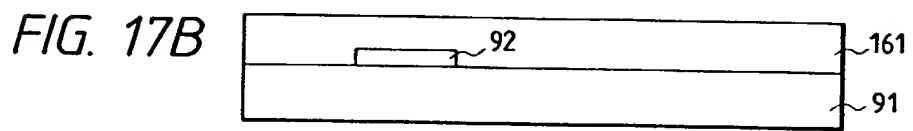
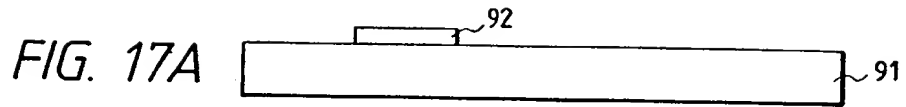


FIG. 19

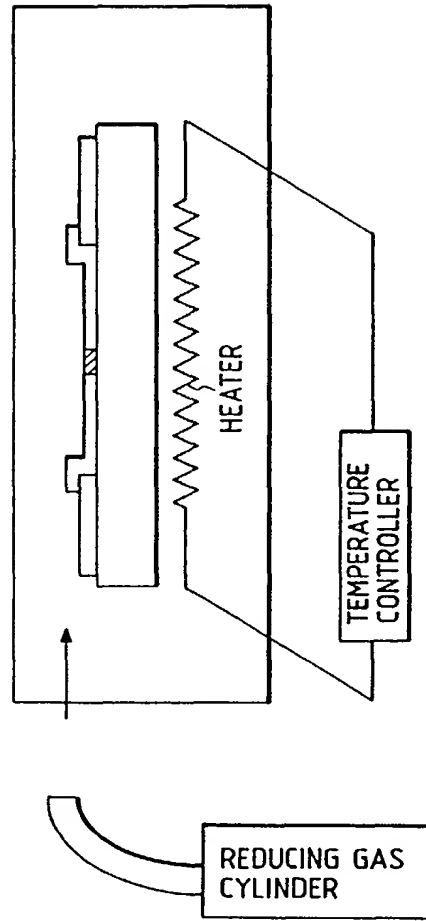


FIG. 20

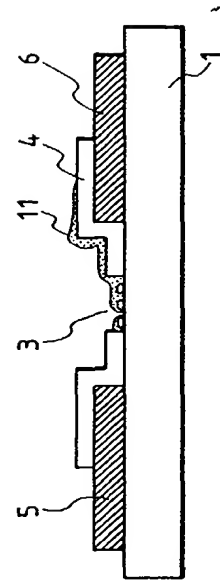


FIG. 21

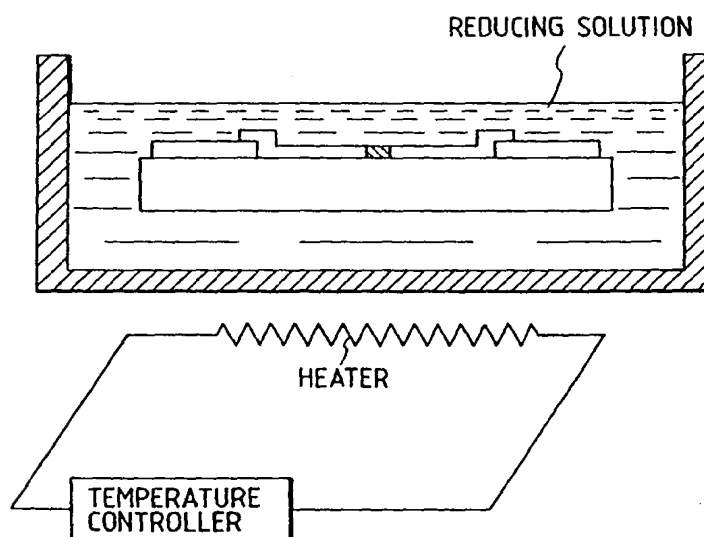


FIG. 22

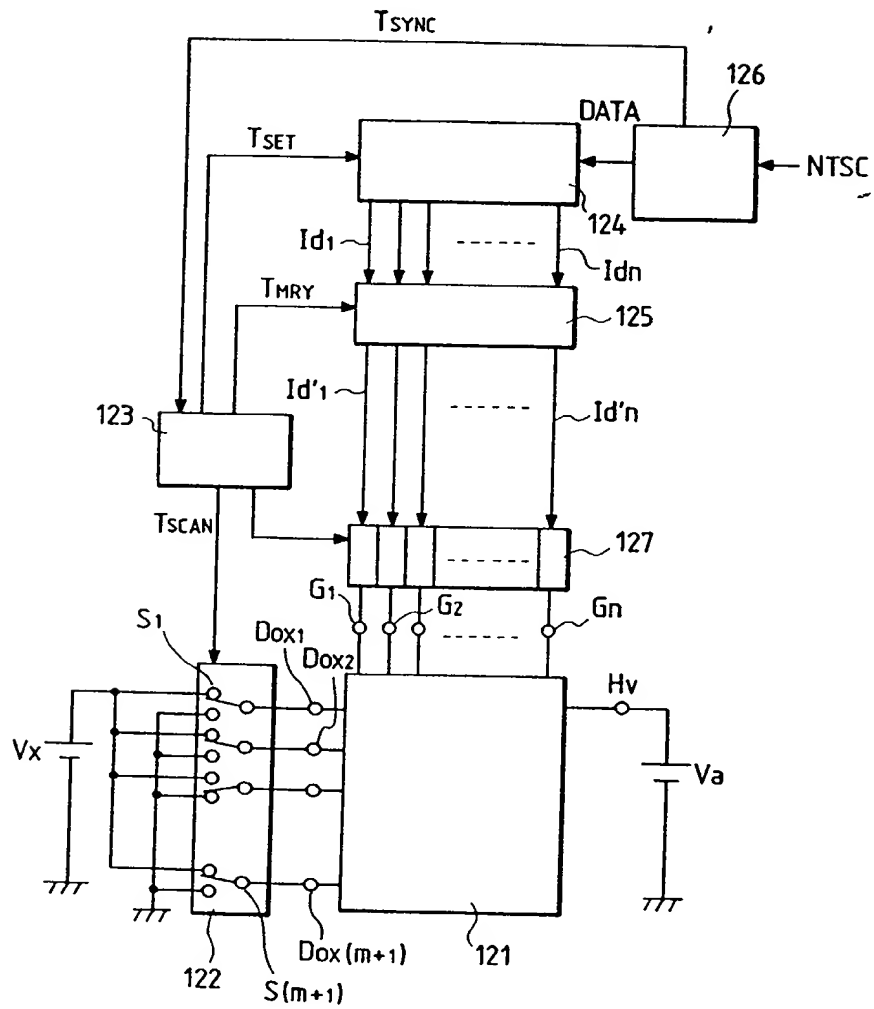


FIG. 23

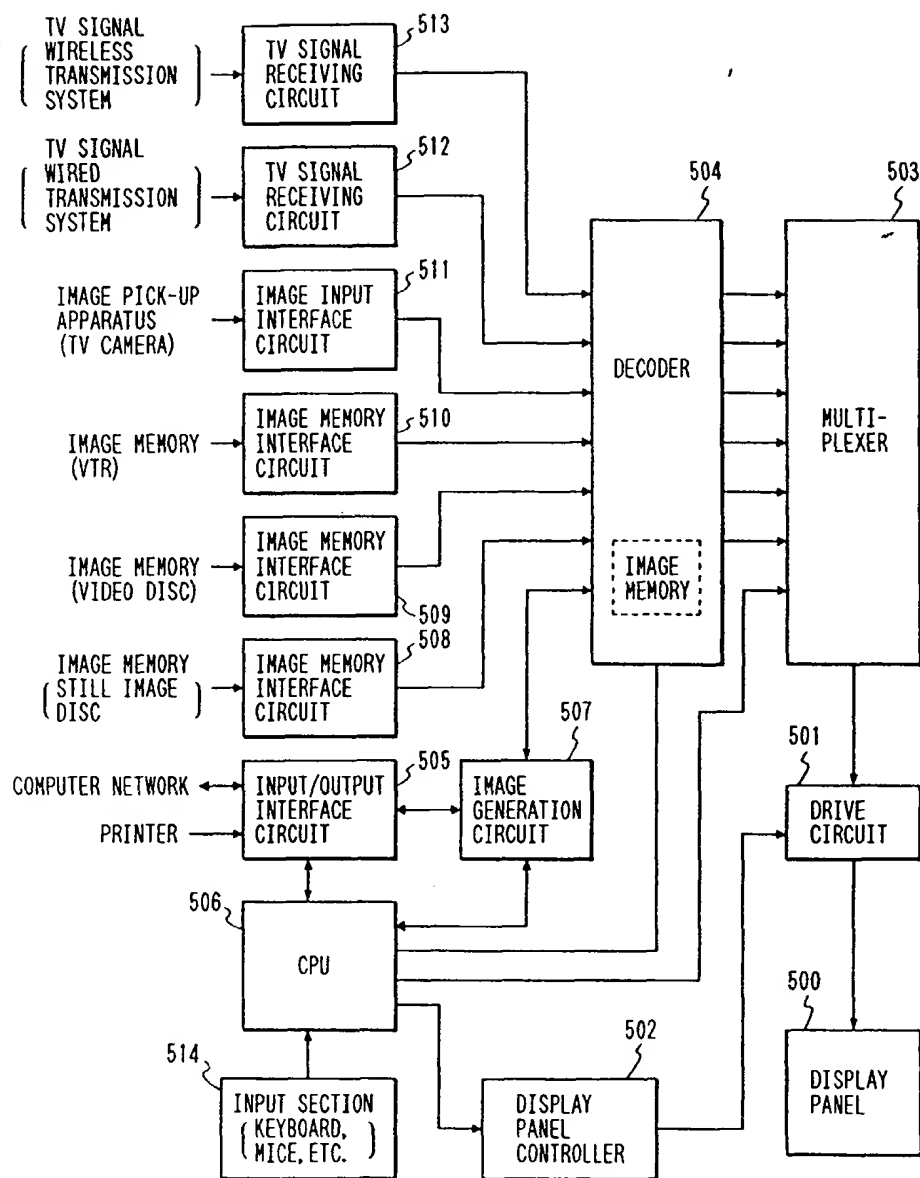


FIG. 24

